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Human Induced Cyclical Erosion Due to Altered Sediment Bypassing Mechanisms of a Barrier Island and the Resultant Impact on the Housing Market

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Human induced cyclical erosion due to altered sediment bypassing mechanisms of a barrier island and the resultant impact on the housing market

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APPROVAL SHEET

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Introduction

Coastal erosion and retreat have tremendous impacts on society, infrastructure and ecosystem functions in the coastal and marine environment. These processes are essential to a range of coastal policy issues since a large fraction of the world's population lives within 150 km of the coast and available sediment to the coast is decreasing globally (Kriesel et al., 2000). Fundamental social- and natural- science questions surround coastal erosion due to insufficient supplies of sediment, accelerated sea-level rise and enhanced storminess.

This study addresses the interplay between Coastal Geology and Marine Policy at the Merrimack River inlet and Plum Island, Massachusetts, in the Gulf of Maine. The Merrimack River mouth has migrated ~3 km since European settlement in New England (Nichols, 1942; FitzGerald 1993; Hein et al., in review). In response to the navigational challenges posed by this dynamic inlet, the United States Army Corps of Engineers (USACE) stabilized the inlet through the construction of two jetties in 1914. Following jetty construction, the northern portion of the island experienced successive cycles of much smaller-scale shifts in shoreline position (~100 m of mean high water) driven by alternating periods of erosion and accretion of roughly 25-30 years.

The Plum Island barrier system has undergone wide-ranging human alterations which, combined with complex climate-change impacts, created new human-induced dynamics for this barrier and its associated inlet system (Hubbard, 1979). Results for the coastal community have been highly damaging, with consequences that impact nearby populations on annual and decadal timescales. Over the last seven years, Plum Island has been in an erosion phase, with more than a dozen homes being destroyed and/or condemned due to erosion (Schworm, 2013). The recent erosion has brought ample media attention to Plum Island, raising questions about coastal policy, specifically with regards to home protection and economic implications for property owners and overseeing government agencies. The contributions of coastal erosion and inundation risk are factors that influence properties, but should also influence policy makers as the economic contributions of factors like shoreline protection, piling construction and relative erosion rate greatly influence the longevity of a property.

Evaluating changes to the coastal environment over multiple timescales, as well as the impacts of those changes on housing prices, provides a multi-disciplinary approach to assess Plum Island erosion from both Geologic and Economic perspectives. This is achieved through the compilation of > 100 years of shoreline change data along Plum Island, and the development of a Hedonic Pricing Model to determine contributing dollar amounts of environmental variables to homes on Plum Island. Modern shoreline-erosion studies (*e.g.*, shoreline mapping, sediment sampling) were used to monitor the short-term (1–2 yrs) impacts of specific erosional events (storms) and management strategies. This combined knowledge provides insights into the nature and degree to which humans altered natural coastal processes and developed feasible management strategies that balance natural processes and the financial contributions of environmental dynamics to the coastal community. Each of these topics will be addressed in separate chapters of this thesis: the first focusing on shoreline change and cyclical erosion, and the second on the economic impact of environmental variables on Plum Island.

Chapter 1 of this thesis, is titled "Multi-scale erosional cycles due to sediment bypassing on a jettied inlet". This study presents a geological assessment of cyclical coastal erosion along the northern Plum Island beach, as induced by the jetties on the Merrimack River Inlet and amplified by groins on the downdrift beach. The study was completed through integration of remote long-term (100 years) shoreline change measurements with a short-term (18 month) compilation of beach surveys. The connections of the two time scales illustrate a conceptual model for a 25–30 year cycle of localized erosion driven by a combination of inlet sediment bypassing and nearshore bar wave refraction, on an otherwise long-term stable barrier island.

Chapter 2 of this thesis, is titled "Evaluating the impact of beach erosion, shoreline protection and piling construction on the housing market". This chapter focuses on the development and results of a hedonic regression model. The model produces perceived values of traditional real estate (beds, lot size, house style, etc.) and environmental variables related to coastal erosion as a portion of the total value of a property. The model output quantified the economic importance of shoreline protection (both public and privately owned structures) and raised piling construction. In addition, the output indicated an insignificance of a time to inundation variable due to the non-uniform shoreline trends on the island, directly in line with the geologic findings in Chapter 1.

Chapter 1:

Multi-scale erosional cycles due to sediment bypassing on a jettied inlet

Abstract

Barrier Islands worldwide are experiencing drastic transformations due to the acceleration in sea-level rise, more frequent severe storms and the adverse effects of anthropogenic shoreline modifications. Barriers are commonly highly engineered at their bisecting tidal inlets, which, when left unaltered, are highly dynamic systems that undergo complex morphologic cycles, restricting the possibility of permanent development. This chapter presents the analysis of an engineered New England barrier and inlet system over historic and recent timescales to characterize complex patterns of shoreline change caused by both natural and anthropogenic drivers. Recent beach sediment volume calculations show erosion of >30,000 m^3 on a 350-m long stretch of beach in just 6 months, followed by recovery associated with the alongshore migration of an erosion hotspot. We couple sediment volume analysis with a 100-year record of changes in the position of the beach high water line in order to develop a comprehensive conceptual model based on sediment bypassing mechanisms and nearshore wave refraction to characterize 25–30-year cycles of hotspot formation, migration and dissipation. This multi-temporal shoreline analysis fully illustrates the dynamics of this coastal system and sheds light on the adverse impacts of engineering structures when employed only as short-term solutions.

Introduction

As of 1992, >75 % of the United States coastline was eroding (Orrin & Thieler, 1992), a figure likely higher today. Many of these vulnerable shorelines are found along barrier islands, which can experience retreat rates as high as 15 m/yr (*e.g.*, the Louisiana coast; Penland, 1985). Barrier Islands compose up to 15% of the world's coasts (Stutz & Pilkey, 2011). The majority formed 3-8 kyr before present (B.P.), upon the slowing of sea-level rise following final retreat of the ice sheets associated with the Wisconsin glaciation (*e.g.,* Timmons et al., 2010; Hein et al., 2012; Wallace & Anderson, 2013). Barrier Islands have been the focus of abundant scientific investigation over the last 40 years, with studies focused on their formation, dynamics and, most notably, finer-scale retreat and erosion (Hoyt, 1967; Leatherman, 1979; Oertel, 1985; Orrin & Thieler, 1992).

Currently there are two primary reasons for coastal erosion on barrier islands: a rise in relative sea level and a decrease of sediment supply to the coast (Syvitski et al., 2005). The importance of changes in relative sea level and sediment supply in coastal equilibrium are further explained by Curray (1964) through examination of the rock record of transgressive (landward shifting) and regressive (seaward shifting) facies sequences based on relative sea level and sediment supply. Fluvial sediment worldwide is limited (80% of pre Anthropocene), largely due to installation of dams, deforestation and urbanization (Syvitski et al., 2005). This sediment deficit is amplified by an acceleration in sea-level rise, up to 0.15 mm/yr^2 in some places along the Gulf and Atlantic coasts of the United States (Kensington & Han, 2014). The combined effect leads to coastal erosion and barrier island retreat.

The process of coastal erosion occurs through many mechanisms and can be a permanent or ephemeral aspect of shoreline processes. Seasonal variation produces stark contrast in winter and summer beach profiles, due to high energy winter storms flattening the beach and storing sediment offshore to be slowly worked back onshore through the summer months (King, 1972). The summer accretion pattern often occurs through the landward migration of ridge and runnel systems. The landward-sloping ridge is reworked by onshore waves as the shore parallel runnel is slowly thinned until the ridge and shoreface weld together (Davis, 1994). If the volume of sediment accreted to the shoreface and beach during summer reworking does not equal that removed by winter storm activity, net erosion occurs. Bruun (1962) illustrated the concept of landward barrier migration in response to sea-level rise, the Bruun Rule, as an empirical relationship indicating landward migration of a barrier proportional to the vertical rise in sea level, indicating that a small increase in sea level can dictate a large landward migration in low-lying areas. The Bruun Rule was later expanded upon by Dean and Maurmeyer (1983) to include the entire barrier system, notably the role of sediment overwash elevating the backbarrier marsh and lagoon environments (FitzGerald, 2008).

The coastal zone in general, and barrier islands in particular, have been highly developed in the last 100 years. Coupled with the dynamic nature of beaches, tidal inlets and barrier islands, as well as the coastal impacts of climate change (*e.g.,* sea-level rise, storms), this has resulted in severe risk to public and private infrastructure. Kriesel et al. (2000) estimated that 25% of all homes within 150 m of the shore may have property losses due to erosion over the next 50 years. To mitigate risk and protect infrastructure investments, communities utilize inlet, dune and shoreline stabilization structures, altering natural processes and occasionally leading to localized exacerbated erosion.

Tidal Inlets and Ebb-Delta Breaching

Tidal inlets are a key component of barrier islands. They are narrow water bodies bisecting adjacent islands and/or mainland which exchange water and sediment from the ocean to a back barrier system (Hayes, 1980). The interaction of waves, tides, sediment exchange with upstream rivers and longshore sediment transport create flood- and ebb- tidal deltas on either end of the main channel (Figure 1). The complex morphology of tidal inlets allows them to store nearshore sediment to be reworked onto the adjacent beaches through inlet sediment bypassing mechanisms (FitzGerald, 1976). Understanding stable inlet dynamics and sediment-transport processes are crucial on developed coasts, where inlets provide harbor access and safe recreational and commercial navigation, and control sediment distribution on adjacent beaches.

Tidal inlet stability and sediment-transport processes have received ample attention in the scientific literature. FitzGerald (2000) described nine different models by which sediment can bypass tidal inlets. Each is active at a given site according to physical regime, sediment availability and source as well as the presence of engineering/mitigation structures. One such model is stable inlet processes, where sediment bypassing occurs through the growth of channel linear bars and subsequent migration and welding to additional swash bars and eventually onshore (Figure 2a). In more tide dominated environments ebb-delta breaching is the prominent bypass model where the ebb-delta becomes hydrologically unstable causing the current inlet throat to migrate, enabling sand sources previously constrained in the ebb-tidal delta and channel linear bars to migrate onshore (Figure 2b). Mesotidal coastal environments are most prone to bypassing via ebb-tidal delta breaching due to the prominent ebb and flood tidal deltas associated with a larger tidal prism and strong fluvial influence. Studies have shown that cycles of sediment bypassing in natural tidal inlets is on the order of 4–8 years from building of the ebb-tidal delta, breaching of the delta through channel avulsion and subsequent bar migration and welding (Fitzgerald, 1984, Guadiano & Kana, 2001). The periodic nature of sediment bypassing commonly drives an alternation between erosion and accretion of downdrift shorelines according to the timing of the sediment bypassing cycle (Guadiano & Kana, 2001).

The mechanisms of ebb-tidal delta breaching are commonly altered once the inlet is hard engineered with jetties and/or terminal groins (Figure 2c). At jettied inlets, the timescale of delta growth, breaching and subsequent onshore bar migration and welding is elongated because the inlet has been extended further offshore and into deeper water. This has been observed at Ocean City Inlet where a cycle of breach, migration and welding was in excess of 40 years (Kraus, 2000, Table 1). Furthermore, these processes were observed to be closely coupled with periodic erosion and accretion cycles along the downdrift shoreline. This is not unique to Ocean City Inlet: structured, mixed-energy inlets around the world have experienced a mix of downdrift and cyclical erosion due to the shift in equilibrium following jetty construction (FitzGerald, 1984; Castelle et al., 2007; Fontolan et al., 2007; Dickson et al., 2009; Galgano, 2009; Garel et al., 2014; Table 1). This study aims to analyze the shoreline change patterns on a downdrift barrier island of an engineered tidal inlet at Plum Island, Massachusetts (the Merrimack River Inlet). Datasets collected over monthly and decadal time scales allow for the full characterization of this inlet and associated downdrift beach, and help to better understand the current and previous shoreline patterns of coastal erosion.

Study Site

Plum Island, the longest barrier island in the Gulf of Maine, is located along the mixed-energy, tide-dominated coast of northeast Massachusetts (Figure 3). It is uncommon among US East Coast barriers in that it is neither heavily nourished nor undergoing landward migration. Its shoreline is highly stable: over the last 150 years, the island has experienced long-term erosion at the statistically insignificant rate of only 0.09 ± 0.6 m/yr (Thieler et al., 2013). Located at the mouth of the Merrimack River, Plum Island is one of a series of five barrier islands, totaling 34 km and fronting the largest marsh system north of Long Island, the *Great Marsh* (Fig. 3).

The Plum Island barrier complex was formed in a setting which experienced rapid, isostatically driven changes in relative sea level following the retreat of the Laurentide ice sheet from northern Massachusetts at 16–17 kyr B.P. (Borns et al. 2004). Upon slowing of RSL rise 6–7 kyr B.P., sediments derived from abundant quartzose sources in the granitic plutons of the White Mountains were delivered to the coast by the Merrimack River. The sediments were subsequently reworked to form a proto-barrier system (Rhodes, 1973; McIntire and Morgan, 1963; Hein et al., 2012, 2014) which gradually migrated landward during a period of relatively rapid RSL rise. Plum Island stabilized in its current position between 4 and 3 ka, and has been largely stable to progradational since (Hein et al., 2012).

Plum Island and the rest of coastal New England were settled by Europeans in the late 1600s. By the 1800s, Newburyport, just upstream of Plum Island along the Merrimack River, became a commercially viable port (Labaree, 1962). At the mouth of the Merrimack River is a dynamic tidal inlet, the Merrimack River Inlet. Since settlement, this inlet, along with the adjacent beach / barrier system, has undergone several periods of inlet migration, spit elongation, ebb-tidal delta breaching, and offshore bar formation, onshore migration, and shoreface welding (Fig. 2; FitzGerald 1993; Hein et al. in review). These processes made the inlet nearly unnavigable, particularly between 1827 and 1851 when a migratory bar, formed from a previous breach in the ebb-tidal delta, accreted onshore, shifting the once southeast-oriented river mouth to its current position (Nichols 1942; FitzGerald 1993). This bar accretion event formed the Right Prong of Plum Island and left the previous river channel to form what is now the "Basin" between the two north prongs on the Island (Fig. 3; FitzGerald 1993).

Jetty construction began on the inlet in 1881 as a response to the navigational problems. The south jetty was completed in 1905 and the north jetty in 1914. These jetties have undergone several periods of major rehabilitation and lengthening; modern lengths are 745 m and 1250 m, respectively (U.S. Army Corps of Engineers, 1917). Since jetty completion, the inlet has been routinely dredged every 3–4 years on average. Greater than 2,000,000 m^3 of sand has been removed between 1937 and 2010 (E. O'Donnell, U.S. Army Corps of Engineers, personal communication). The presence of ebb-oriented bedforms within the Merrimack River Inlet, the southeasterly orientation of the inlet ebb-tidal delta, the dearth of sand on the updrift shelf north of the inlet, increased sedimentologic maturity alongshore south of the inlet, and the thickening package of Holocene sand on the shallow shelf south along Plum Island have all been cited as evidence of the Merrimack River continuing to provide abundant sand-sized sediment to Plum Island (FitzGerald et al., 1994; Hein et al., 2012, 2014). It is thus likely that the average of 30,000 m^3 of sand per year that has been dredged from the inlet is almost all derived from the Merrimack River itself, rather than from an alongshore or offshore source.

Following jetty construction, the northern 3 km of Plum Island has undergone intermittent cycles of much smaller-scale erosion and accretion (~50-100 m lateral shifts in the position of the beach high-water line). Localized erosion in the last decade has prompted private homeowners, as well as federal, state, and local governments, to employ a variety of mitigation strategies as surge protection for public and private property. This includes the construction of four shore-perpendicular groins along a 500 m stretch of the beach in the 1950s, and more recently (2008–2014) coir bags and rip-rap revetments to reinforce the dunes (Table 2). Each method has shown varying degrees of success, however more than a dozen houses have been lost to coastal erosion over the past seven years.

Methods

This study employs data collected on two separate time scales, allowing for the correlation of the long and short-term records of change along northern Plum Island. GIS analysis of 100 years of shoreline positions derived from historic documents and imagery provide insight into cycles of shoreline erosion and accretion associated with inlet dynamics. Monthly beach surveys conducted using a Real-Time Kinematic Global Positioning Systems (RTK-GPS) allow for the fine-scale analysis of shoreline position and beach volume variability over monthly to seasonal timescales.

Historical Shoreline Change

Geographic Information Systems (GIS) digital mapping was used to assess the position of the high-water line (HWL) along the northern 2.8 km of Plum Island over the last 100 years. This section of Plum Island, located most proximal to the Merrimack River Inlet, is the only developed section of the island. It is also the only part of the island to have experienced historic erosion; the southern ~80% of the island has been stable (within mapping error) for the last 150 years (Thieler et al., 2013). Along the northern part of the island, six shoreline sectors were identified for particular focus of analyses; these have been termed (1) Right Prong, (2) Tombolo, (3) Center Island, (4) Annapolis Way, (5) Fordham Way, and (6) Refuge (Figure 3).

High-water lines were mapped following the conventions of the US Geological Survey described by Thieler et al. (2013). Two techniques were used to consistently identify the HWL on recent (1970s to present) satellite and aerial imagery. First, where possible, the division between dark and light sands on the beach was mapped, indicating wave run-up during the previous high tide. In the cases where the sand division was either not apparent or the imagery resolution was too poor, the HWL was mapped as the seaward edge of the wrack line, as per Thieler et al. (2013). Historical shorelines (pre-satellite imagery) were derived from georeferenced NOAA T-sheets. Early T-sheets do not have the detail to discern the high water line other than using the drawn boundary of land and water, this is interpreted as a high water line, but with a higher error than other sources (Thieler et al., 2013; Table 3).

Uncertainty in mapped HWL positions has been addressed in previous shoreline mapping efforts (Hapke et al. 2011; Thieler et al. 2013) through incorporation into a mapping uncertainty which also accounts for mapping resolution, historical uncertainty, and, if applicable, rectification image uncertainty. These are treated as a compilation for each shoreline, thereby creating a single numeric uncertainty for each paleo-shoreline position. Horizontal shoreline mapping uncertainty is in a range of 01.0 – 4.3 m depending on the source. Even the larger error value is well within the range of horizontal shoreline position change (10s of meters between mapped years).

Beach Surveys

The short-term shoreline analysis of northern Plum Island is composed of RTK-GPS beach surveys collected monthly between December 2013 and January 2015, and a final survey in March 2015. A Topcon Hiper II RTK-GPS was used to collect continuous X, Y, Z position data along and across the northern 2.8 km of the Plum Island beach. Each survey consisted of approximately shore-parallel transects along the dune toe, mid beach and low tide. Crossing transects were run intermittently along the entire beach connecting these parallel transects in order to correlate across them. Surveying was done by walking the beach, holding the RTK rover upright and collecting continuous data every 1m for a total of ~15,000 data points per month.

The resulting RTK-GPS data were post-processed using Microsoft Excel and then interpolated via variogram-based kriging in a GIS framework to create a three-dimensional Digital Terrain Model (DTM) for the entire survey area. Post-processing involved calibrating all X, Y and Z survey values by the base station position to increase precision of the survey points. Once calibrated the survey points are opened in ArcGIS to delete any outliers (points not in the survey area or on structures). The kriging interpolation variogram model is based on the spatial autocorrelation between data points. This model then predicts the unknown values to complete the interpolation surface (Stein, 2012). This multi-step process allows the interpolation to reflect a directional bias, in this case the constant sloping surface of a beach face. Production of these DTMs from 15 months allowed for the comparison of sediment budgets along the beach throughout the year, as well as the analysis of areas of severe erosion or accretion and seasonal variation to the beach profile and morphology.

The monthly RTK data has an associated average error of 0.028 m horizontally and 0.048 m vertically from sampling. In creation of the DTMs there is also an error associated with the GIS interpolation. The root mean square errors for entire beach sediment volumes is a range of 0.013-0.021, depending on the survey month. This high accuracy is due to the large number of collection points (minimum of 13,000) in each survey. The error for the sediment volume DTMs is ±25,000 m^3, less than 5% of the minimum monthly beach volume (min 605,000 m^3). A maximum error of ±5% is assumed and therefore no comparisons are made or major changes cited in volumes of less than 10% to ensure significant morphologic change outside of error bounds.

Results

The results for both the historical GIS and short term RTK-GPS mapping are compiled to correlate two time scales of shoreline change along the inlet-proximal section of northern Plum Island. The historical record is an assemblage of 13 high water shorelines (1912, 1928, 1953, 1970, 1974, 1976, 1978, 1990, 1991, 1994, 2005, 2008 & 2013, info on all shoreline years in Table 3). The short term record consists of every month from December 2013 to January 2015, plus an additional survey in March 2015.

Historical Shoreline Change

Historical shoreline-change analysis reveals that there have been consistent fluctuations in shoreline (HWL) position between a long-term steady-state equilibrium position and an erosive position, located 80–100 m landward of the long-term position (Table 2, Figure 4). Shifts from the steady state position to the landward, erosive position occur once every 25–30 years. This position of the erosive shoreline is not consistent along the entire 3 km of the beach, but rather localized along an alongshore distance of *ca.* 300–800 m. Such a region of focused erosion is generally referred to in the literature as a "hot spot" (Gaudiana & Kraus, 2001). The identification of historical erosion along only localized sections of the beach at a given time is may reflect the temporal migration of this hot spot: historical shorelines represent a snapshot in time. For example, a ~100 m (shore-perpendicular) erosive shoreline occurred in 1912, 1928, 1953, 1976-78 and 2008-2014, but only in small sections of beach (200-500 m) and not the entire shoreline (Table 2). Focusing on the last 15 years, two of these instances of localized erosion have led to 95 m and 85 m of erosion along Center Island and Annapolis Way, respectively (Figure 5).

Beach Survey Results

Monthly beach surveys provide for the analysis of beach morphology changes along both the entire section of the studied beach and in regions subdivided between structured sections dictated by groin placement. These surveys also allow for the determination of the degree of seasonality and monthly variability present in this system. This is quite important in analyzing patterns of shoreline change to ensure we are capturing morphological anomalies and not the expected variability associated with seasonal profile changes and/or random storms throughout the year.

To normalize the subdivided areas of interest we first organize the monthly sediment volumes for the entire 2.8-km of the northern Plum Island beach as well as five sections of the beach (Tombolo, Center Island, Annapolis Way, Fordham Way and Refuge, Figure 3). To compare subsections of different lengths of beach, we look at the two-dimensional change in cross shore profile volume (m^3/m) between surveys. As expected, this reveals that the entire beach exhibits a high degree of seasonal variability (Figure 6). To account for this seasonality and examine alongshore trends in erosion/accretion during the study period, beach volumes are normalized by dividing the volume of each subsection by the volumetric change of the entire beach for that same period of time (Figure 7).

The entire beach sediment volume ranges from 605,000 m^3 to 1,025,000 m^3. The largest individual change between surveys occurred between November 2014 and December 2014, when beach volume decreased by 239,000 m^3. This is aligned with the high wave activity during late November, 2014 (Figure 6 & 7). The five subsections of interest all have different lengths, so evaluating one subsection to another through a volume/distance (m^3/m) metric allows for the most equal comparison. The largest month-to-month changes for Tombolo, Center Island, Annapolis Way, Fordham Way and Refuge sections are 70 m^3/m (Jan 15), 140 m^3/m (Jan 14), -75 m^3/m (Sep 14), 175 m^3/m (Nov 14) and -139 m^3/m (Mar 15), respectively. Full sediment volumes and volume changes between each survey are presented in Tables 4 and 5.

The largest spatial variation observed during the study period was between the months of August and September along Annapolis Way and Fordham Way; in fact, during this period Annapolis Way experienced *ca.* 25,500 m^3 (70 m^3/m) of accretion while Fordham Way simultaneously experienced *ca.* 12,000 m^3 (87 m^3/m) of net sediment loss. There were no major storm events during this time but a spring tide of 3.0 m (average 2.7 m) occurred in late August. Local homeowners believed the recent high tide could be a major driver, however the high tide was no different than the highs for other months (daily high tides, Figure 6 & 7). The beach fronting Annapolis Way continued to grow following this shift: between September 2014 and March 2015, *ca.* 30,000 m^3 (82 m^3/m) of sediment accreted along Annapolis Way (Figure 6). During this same six month period, the Fordham Way experienced gradual accretion (8,000 m^3, or 57 m^3/m). This observed shift in the focus of erosion occurred rapidly from September to November, and then remained steady until March 2015 (Table 4, Figure 8 & 9). This accretion occurred during the months of heaviest wave activity (Figures 6 & 7), while the summer erosion occurred in quiet weather conditions indicating other factors driving beach behavior.

Discussion

Cyclical Hotspot Erosion and Migration

Long-term records of HWL positions along northern Plum Island coupled with short-term, high-resolution mapping of beach sediment volumes reveal distinct patterns of shoreline change over multiple timescales. The HWL mapping displayed the cyclical nature of the Plum Island shoreline and recurring pattern of erosive shoreline (~100m shore-perpendicular) followed by steady-state position (Figure 4). The historic shoreline patterns prompted the analysis of the last 7 years of high frequency satellite imagery (Figure 5) and monthly beach surveys with detailed observations to determine the fine scale changes occurring in a period of erosion hotspot migration (Table 6).

Over the shorter term, it is revealed that these trends are attributable to the formation and southerly migration of a hotspot of erosion, ~200-300 m long and eroded ~100 m from the steady-state shoreline position. The hotspots also tend to be on the north side of groins from the combination of fair weather driven northern transport and wave refraction around the ebb-tidal delta and offshore bar from high energy northeast storms (Hubbard, 1979). The most recent period of hotspot formation and migration started in 2007 and was focused immediately north of the Center Island groin (Figure 5). During this period, the shoreline north of the groin shifted ~90 m landward. By the start of surveys in December 2013, the hotspot had shifted entirely to the beach fronting Annapolis Way, while the Center Island beach had prograded to its approximate long-term equilibrium position (Figure 5). In addition to the hotspot shift, there was an analogous shift in the position of the offshore bar from offshore of the Center Island groin to offshore of the Annapolis Way groin (Table 6). This shift does not appear to have been gradual, but rather occurred as a jump in which the hotspot shifted over the Center Island groin south to Annapolis Way (Figure 5). This observed mechanism reveals the role of groins along this beach in focusing erosion and controlling the location of the hotspot. In addition to groins the rip-rap revetments along Annapolis Way create scour of the beach from incident wave energy at the base of revetments.

One such shift in the hotspot location was observed over the short-term survey period. This process is best illustrated in the months of September and October 2014 along Annapolis Way and Fordham Way. The Annapolis Way section of shoreline was more eroded in September than any other survey during the 15 month period (Figure 8 & 9). The section is entirely armored with rip-rap upon which waves were crashing as early as mid-tide; no beach was present at high tide. By November the beach HWL had prograded 20 m seaward of the revetment, providing a new berm and dune toe line sub aerially throughout the tidal cycle. Growth of Annapolis Way continued until our last survey in March where there was an increase in beach slope, area of beach above water at high tide and overall sediment volume (Figure 8 & 9).

The changes in sediment volume observed along Annapolis Way during the late 2014 to early 2015 period cannot be attributed to seasonality because of the extent of erosion in September 2014 (Figure 8 & 9). This is seen because the beach profile in September 2014 is one with a typical winter slope, while the profile of the March 2015 section of beach has a characteristically summer slope (Figure 9). This variation in slope is the opposite of seasonal beach profiles, which are marked by a sloping beach with a strong berm in the summer, followed by a flatter, low tide terrace with very little if any berm in the winter (King, 1972). The difference in traditional seasonal beach profiles is due to wave conditions characteristic to each season. The summer is characterized by consistent small- to medium- sized swell that slowly over a ~6 month period build a beach vertically, which results in a steeper shore face and a well-developed berm. The winter wave climate is much more severe with stronger and more interspersed wave activity. The strong, storm-derived waves break down the summer profile to create a low sloped beach face with little to no berm. However, in most cases the sand stays within the littoral cell, commonly in a subtidal nearshore bar, which will then migrate landward and be reincorporated back onto the beach during the summer season. The summer of 2014 did not have any notable storms, but did have a spring high tide (3 m high tide, average is 2.7 m) in mid-August, two weeks before the September 2014 survey. In this case, the sediment is not being re-appropriated for later in the year: this is a highly eroded shoreline at the peak of when this should be a healthy beach. Therefore, it is concluded that there is an external forcing causing the erosion and subsequent recovery of the Annapolis Way beach: hotspot migration.

The hotspot erosion on Plum Island is closely linked to the relative positions of the ebb-tidal delta (ETD), the offshore bar(s), which spans some or all of the ~2km south from the ETD until merging eventually with the subtidal bar which stays consistently 100-200m offshore the remaining length of Plum Island. Southerly migration of the hotspot mimics the alongshore migration of the offshore bar still moving south- and west-ward, while slowly accreting onto the downdrift beach (Figure 10). This is evidenced both by the rapid recovery of the Annapolis Way beach and the erosion of the beach further south in the Fordham Way and Refuge subsections. In both scenarios, as well as the conditions observed in 2008 at center Island (Figure 5, Table 6), the erosion is pinned on the north side of a groin, destroying any previous berm, and creating a shallow beach from low tide to the dune toe with very little beach left at high tide. In the months following conclusion of beach surveys (between March 2015 and most recent observations in August 2015), the Annapolis Way beach has again undergone erosion proximal to the Annapolis Way Groin. Thus, it is likely that the hotspot has not entirely shifted south to Fordham Way, and instead is pinned by this groin. Without the groin it is likely that the hotspot would be wider and centered further south. Based on observed trends over the past several years, it is anticipated that the hotspot will shift entirely to Fordham Way in the near future, mimicking the southern migration of the adjacent offshore bar.

Conceptual Model of Cyclical Erosion on Plum Island

Observed patterns of cyclical erosion along northern Plum Island can be directly attributed to the emplacement of jetties at the Merrimack River Inlet, and is exacerbated by hard structures intended to provide shoreline protection on the downdrift beach. This process begins with the lateral and southerly growth of the ebb-tidal delta from the sediment exported by the Merrimack River, the major sediment source to Plum Island. As the ebb-tidal delta grows and expands it eventually becomes hydrologically unstable and will export sand to the offshore bar through a combination of stable inlet processes and outer channel shifting (Figure 2). Changes to the morphology of the offshore bar are now driven by the dominant northeast swell, and the bar migrates south and west toward the beach. However, the ebb-tidal delta is a large morphologic feature as a result of its position further offshore in deeper water due to the two jetties on the river.

The offshore bar stretches roughly parallel to the coast and at times is ~1000-1800 m long and as far as 600 m offshore. Monthly visual observations coinciding with beach surveys throughout 2014 revealed that the bar was at times subaerially exposed at low tide. Even when underwater, small waves were commonly observed breaking over the bar. The ETB moves with the dominant swell along the shore but the incident wave energy causes the wave to refract and curve through the southern break in the bar (approximately the position where the ETB merges with a shore-parallel subtidal bar located 100-200 m offshore of the low-tide line and which extends nearly continuously along the southern 15 km of Plum Island). "Break in Bar" erosion has been documented in numerous locations, although there have been no detailed studies on its underlying mechanisms (Guadiano and Kraus, 2001). Wave refraction dissipates energy behind the bar and deposits sand in the nearshore between the bar and the beach. If the bar resides in a single location for a long enough time, this refraction will starve the section of beach parallel to the break in the bar, resulting in significant erosion.

If this process were to happen on a natural beach, there would be short-lived erosion if any in the area parallel to the bar. We have observed this in historical shorelines in the Tombolo section of the Plum Island beach. Here, there are no proximal groins and the beach response is to prograde, creating a wide beach and low tide terrace, which are together ~150% larger than the adjacent beach. The area of this accretion is highly localized (~200–400 m alongshore), similar to the erosion hotspot. This beach morphology was observed in 2004, prior to the recent erosion. The offshore bar at the time was parallel to the Tombolo area, ~800 m north of the Center Island Groin (Figure 10: 2&3). Although, a similar accretion pattern was seen in 2008 during hotspot erosion at Center Island indicating the strong wave refraction around the bar depositing ample sand on either end of the 600m Center Island subsection (Figure 5).

Hot-Spot Erosion and the Impact of Jettied Inlets

Hot-spot erosion has frequently been associated with structured tidal inlets due to inlet sediment bypassing mechanisms acting on fluvial- and longshore-transport–derived sediment (Table 1). The best documented study of this process acting on a structured inlet is that of Kraus (2000), studying Ocean City inlet. Here, a volumetric assessment of the inlet ebb-tidal delta, migratory bar, and downdrift beach showed an erosion/accretion cycle of 40 years. This is a longer cycle than observed on Plum Island.

Intermittent cycles of erosion and accretion have also been recorded on the downdrift beach of the Guadiana Estuary, Portugal. These cycles are approximately 15 years and extend as far as 3 km east (downdrift) of the inlet (Garel et al., 2014). Here, this process was attributed entirely to sediment bypassing. Both Ocean City and Guadiana estuary sites have similar physical regimes to Plum Island (~2+ m tides and ~1+ m waves) but vastly different volumes of fluvial sediment input: at Plum Island, the Merrimack River provides a substantial proximal sediment source (*ca.* 30,000 m^3/yr based on extrapolation from inlet dredge records). Ocean City Inlet drains a tidal backbarrier and receives limited to no terrestrial sediment. The larger sediment volume and higher energy physical regime dictate smaller cycles on Plum Island due to more sediment being exported from the river and bypassed to the downdrift coast at a faster rate than in Ocean City (Table 1). By contrast, the Guadiana Estuary receives a fluvial sediment load on the order of ten times that of Plum Island (Garel, 2014). In addition, the jetties at Guadiana Estuary are more than twice the length of the Merrimack River Inlet jetties. This drives the erosion hotspot 1.5 times further downdrift (3 km as opposed to 2 km) than is observed on Plum Island (Table 1). The combination of increased sediment load and situation of the ebb-tidal delta further offshore at Guadiana lead to larger scale erosion cycles geographically, although they have been documented to occur over a shorter time frame (~15 yrs).

A second variety of hotspot erosion observed at tidal inlets is propagated erosion migrating along the downdrift beach (Table 1). For example, Saco Bay, Maine has a large jetty system at the mouth of the Saco River; the downdrift beach has experienced erosion rates of 0.6 –1.0 m/yr on average (Dickson et al., 2009). The beach 5–6 km downdrift of the inlet is eroding at up to 2.5 m/yr. This is also the current extent of rip-rap armoring, which has been installed progressively further downdrift from the inlet in response to the erosion. This propagating erosion is likely due, at least in part, to the high scour resulting from the transition of revetment to natural beach and the starvation of the downdrift beach caused by the cutting off of the updrift sediment supply through beach armoring (Dickson et al., 2009). Likewise, severe scour occurred in fall 2014 on Plum Island between the newly installed revetment walls and groins installed during the period of erosion in the 1970s. However, unlike in Saco Bay, erosion has not yet extended past the extent of the revetment walls on Plum Island.

Similar results have been seen at Moriches Inlet on Fire Island, NY, where multiple small sections (arcs) of erosion are separated by nodal points, with decreasing magnitude from the inlet (Galgano, 2009). The erosion arcs vary in magnitude, with rates up to 4 m/yr occurring as far as 1000 m downdrift. This has also been attributed to sediment bypass periodicity around the jettied inlet. However, unlike at Plum Island, where the erosion hotspot has migrated ~500 m over the last 7 years through rapid shifts in position controlled by groins, hotspot migration along Fire Island beach – which contains no such groins – is smooth and gradual (Table 1). This thus highlights the role played on Plum Island of the other engineering structures: the focusing of the erosion hot spot in a given location between groins likely exacerbates that erosion in the short term by focusing break-in-bar wave energy along a narrower section of the beach than would otherwise be the case without these additional structures.

The cycles of erosion and accretion at Saco Bay and Moriches Inlet also have one other notable difference from Plum Island which is the large differences in tidal ranges, which are 3.5 m in Saco Bay and < 1 m at Moriches Inlet. The differences in tide range - whether microtidal or macrotidal – cause different cycles than those multi-decadal cycles observed at Plum Island and other mesotidal environments (Table 1).

Conclusions and Implications

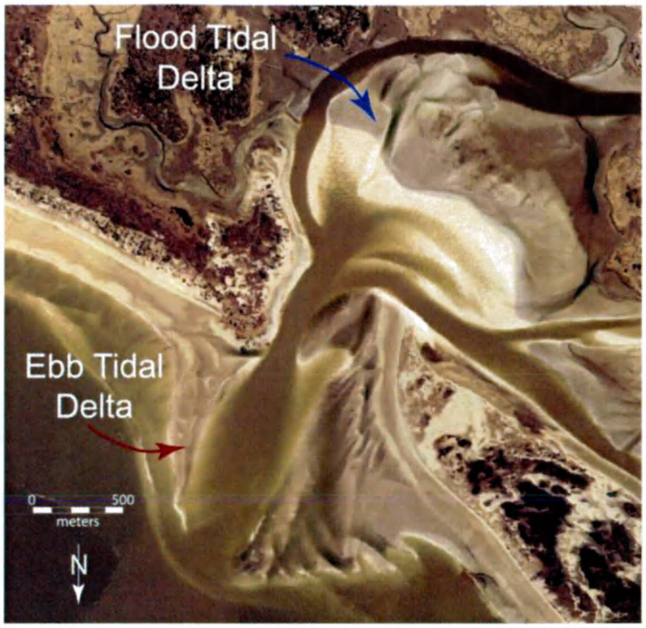
This study combines long-term (100 years) mapping of the high-water line position and short-term (18 months), monthly, three-dimensional surveys of the developed beach of northern Plum Island (Massachusetts). This beach, located immediately downdrift of a jettied inlet, has undergone several periods of severe shoreline erosion with a roughly 25–40 year cyclicity, followed by accretion to a long-term stable, equilibrium shoreline position. These periods of erosion are controlled, in part, by the influence of beach structure such as jetties, revetments, and groins, which together alter sedimentation patterns along the beach. Storm waves refracted around the unnaturally large and offshore ebb-tidal delta (position determined in part by the large jetties holding in place the inlet) interact with the groins and revetments, locally starving small sections of beach (erosion hotspots). These generally are found on the north side of a groin, reflecting the dominant localized northward transport. Hotspot erosion occurs when the southern extent of the offshore bar is parallel with a groin. The position of the groin in relation to the bar inhibits refraction transport around the southern extent of the bar. Any sediment refracting around the bar is blocked by the south side of the groin providing a healthy beach on the south side but starves the beach on the northern side. In addition to the groin exacerbating the erosion hotspot it also acts as a pinning point that keeps the erosion in one place over a small range of sand bar positions offshore. This results in the erosion hotspot staying in a single location for 1–2 years while the bar is continually migrating, until the point that the bar is far enough south that wave energy from the north will provide sediment to the site of erosion, causing a return towards accretion.

Engineering solutions for navigation purposes can have substantial consequences on adjacent beaches because hard structures tend to alter the natural dynamics of coastal systems, resulting in exacerbated erosion. While processes such as the role of seawalls cutting off erosion-derived sediment from downdrift beaches is well documented and widely understood, the complex downdrift impacts of engineering structures at tidal inlets remains relatively understudied. The presence of large jetties shift what would be a dynamic natural equilibrium cycle to a larger and deeper location for the ebb-tidal delta, resulting in cycles of erosion and accretion similar to those observed at natural inlets, but on larger spatial and temporal scales. This tends to enhance the severity of beach impacts of natural inlet sediment bypassing. Plum Island is an important case illustrating that, under certain physical conditions and sediment availability, a beach can be healthy and stable; however, due to engineering practices meant to stabilize some portion of that beach, periodic erosion can nonetheless create short-term management and policy issues for beach users and homeowners.

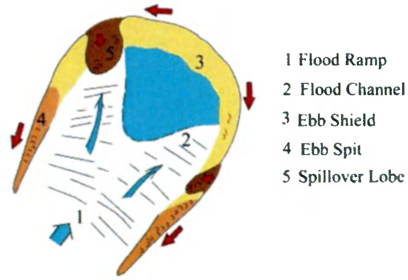
The takeaways of engineering miscues and long-term shoreline stability can be applied to mesotidal inlet and beach environments globally. Currently, mitigation strategies such as hard structures to constrict, control and maintain coastal and barrier ecosystems are the norm. However, this study shows that engineers, geologists and policy makers need a multi-temporal understanding of shoreline change, longshore and downdrift impacts, and the dynamics of interconnected sub- and supra- tidal beach environments to appropriately apply any mitigation structures. A short term fix, such as installation of a groin or revetment wall, may have unintended adverse effects in the future. Many systems, like Plum Island, are highly dynamic and undergo periods of erosion followed by periods of accretion and growth, which can occur on seasonal, annual, decadal or multi-decadal scales. Determining the patterns of cyclicity on a beach are crucial to implementing the appropriate mitigation strategy, otherwise there will likely be adverse effects in the future like we have seen on Plum Island with the use of groins and revetments.

Figure 1: Morphology of a tidal inlet with flood and ebb tidal deltas (FitzGerald et al., 2012). Photograph highlights the prominent channel margin linear bars and swash bars migrating onshore on the adjacent shorelines.

Essex Inlet



Flood Tidal Delta



Ebb Tidal Delta

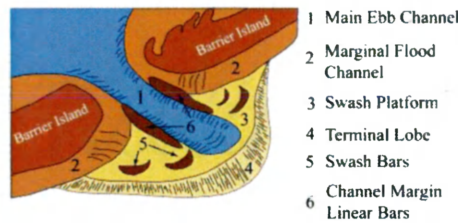


Figure 2: Three sediment bypassing mechanisms at tidal inlets: stable inlet processes, ebb-tidal delta breaching and outer channel shifting at jettied inlets (adapted from FitzGerald, 1993 and FitzGerald et al., 2000, 2012. Attributes from each mechanism partially characterize the sediment bypassing patterns observed at the Merrimack River Inlet.

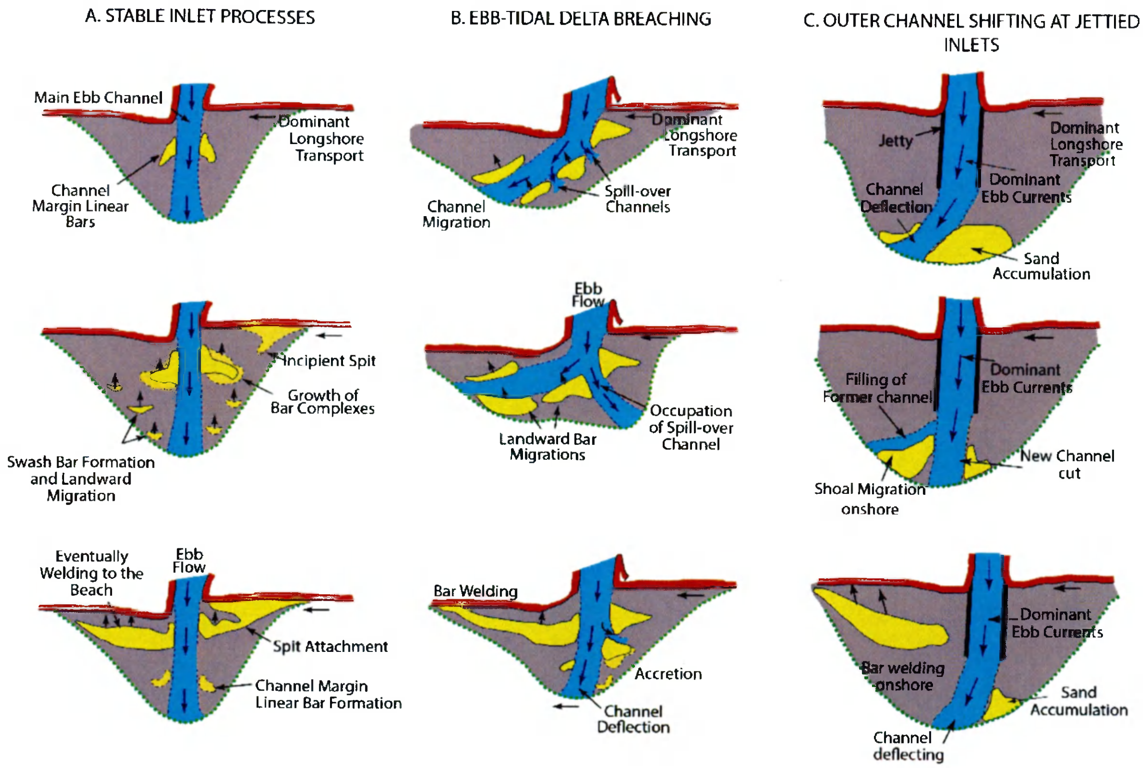

A. STABLE INLET PROCESSES
B. EBB-TIDAL DELTA BREACHING
C. OUTER CHANNEL SHIFTING AT JETTIED INLETS
Main Ebb Channel
Dominant Longshore Transport
Channel Margin Linear Bars
Incipient Spit
Growth of Bar Complexes
Swash Bar Formation and Landward Migration
Eventually Welding to the Beach
Ebb Flow
Spit Attachment
Channel Margin Linear Bar Formation
Dominant Longshore Transport
Spill-over Channels
Channel Migration
Ebb Flow
Occupation of Spill-over Channel
Landward Bar Migrations
Bar Welding
Accretion
Channel Deflection
Jetty
Dominant Longshore Transport
Dominant Ebb Currents
Channel Deflection
Sand Accumulation
Filling of Former channel
Dominant Ebb Currents
New Channel cut
Shoal Migration onshore
Dominant Ebb Currents
Bar welding onshore
Sand Accumulation
Channel deflecting

Figure 3: Plum Island, Massachusetts is a 17 km long barrier island located in the western Gulf of Maine (location in inset box in lower right). The southern 14 km of the island has been stable over the last 150 years, but the northern 3 km of the island (inset) has undergone periods of cyclical erosion and accretion following the construction of jetties at the mouth of the Merrimack River in the late 1800s. Sub-sections of the beach identified in the inset image are those discussed in the text.

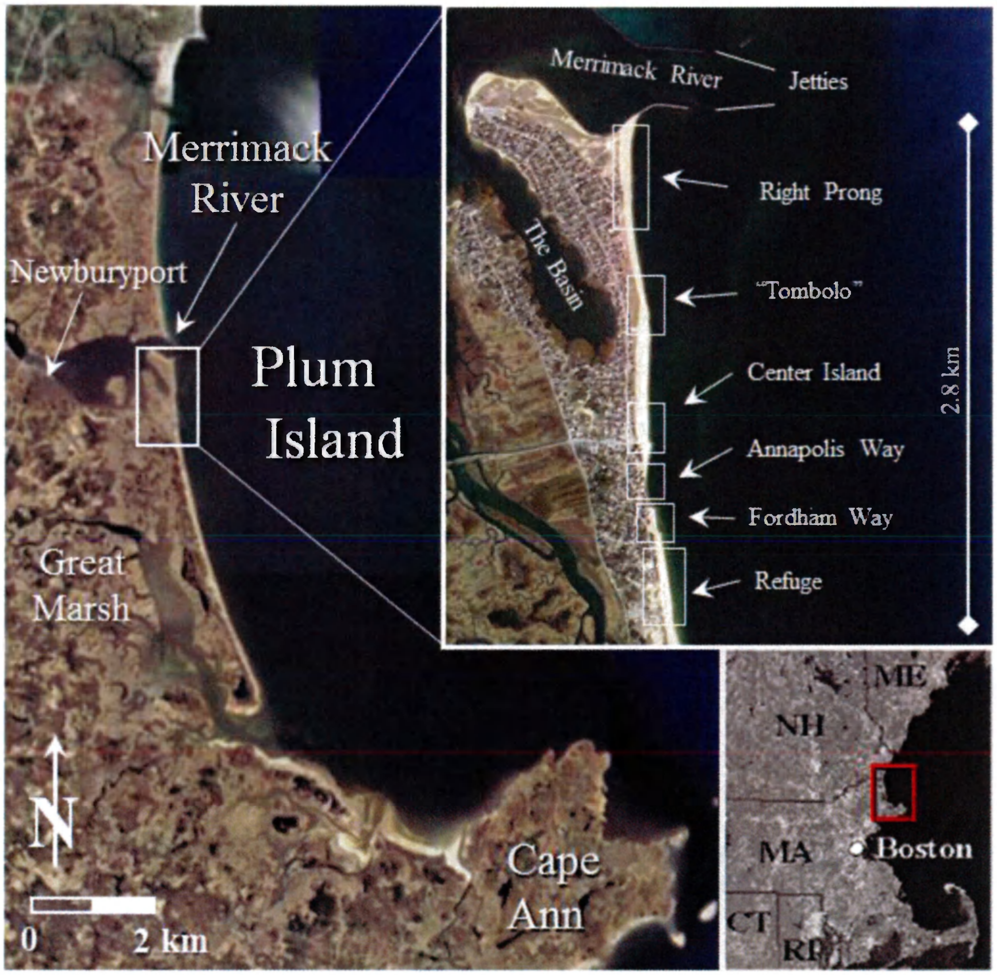

Merrimack River
Newburyport
Plum Island
Great Marsh
Cape Ann
N
0
2 km
Merrimack River
Jetties
Right Prong
The Basin
"Tombolo"
Center Island
Annapolis Way
Fordham Way
Refuge
2.8 km
ME
NH
MA
Boston
CT
RI

Figure 4: Historical shoreline positions along northern Plum Island through time. During eight of the mapped periods, including in 1912, immediately following jetty construction, the shoreline was located within the steady-state position. There were five alternating periods of minimal to intense erosion over the last 100 years.

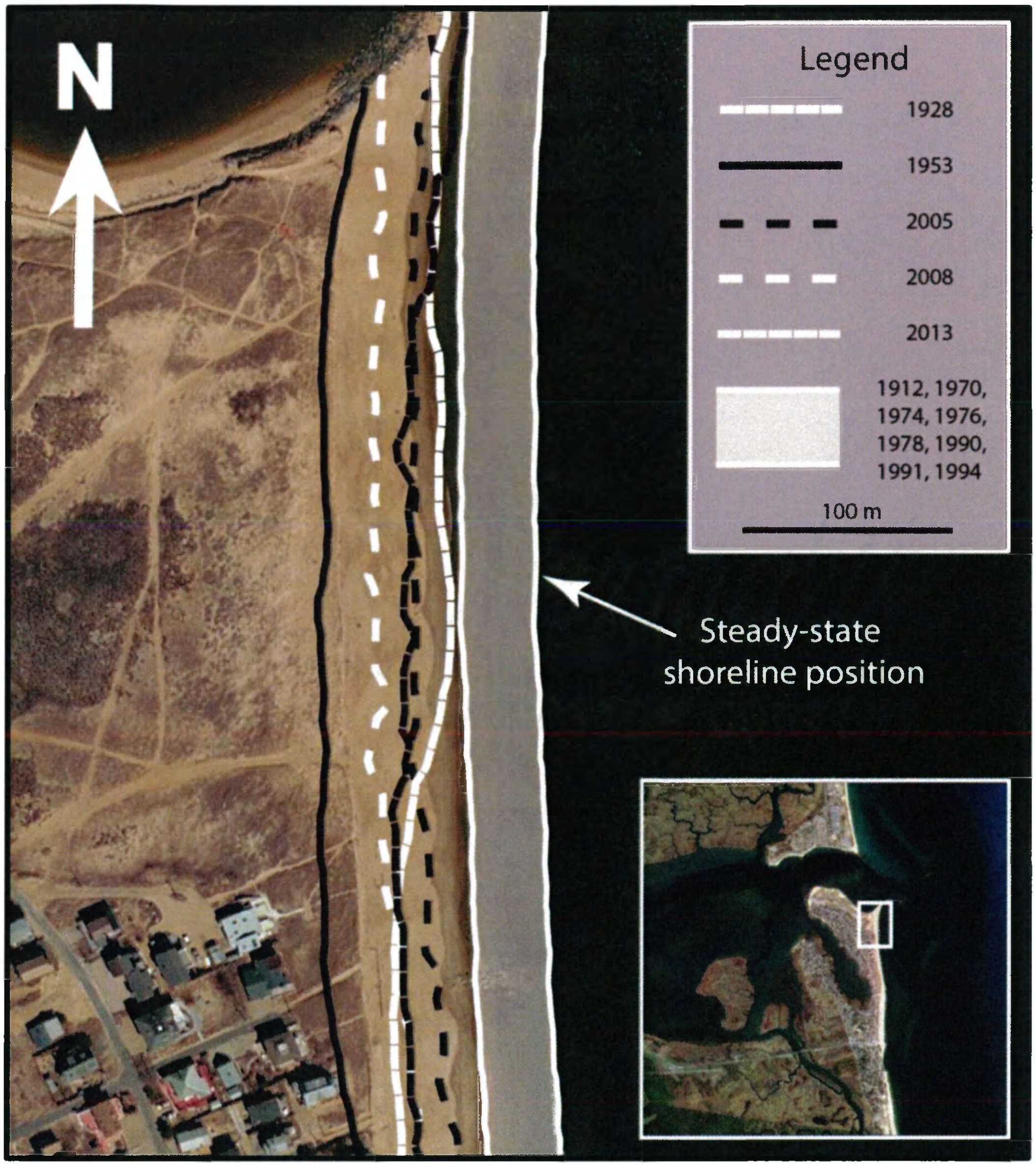
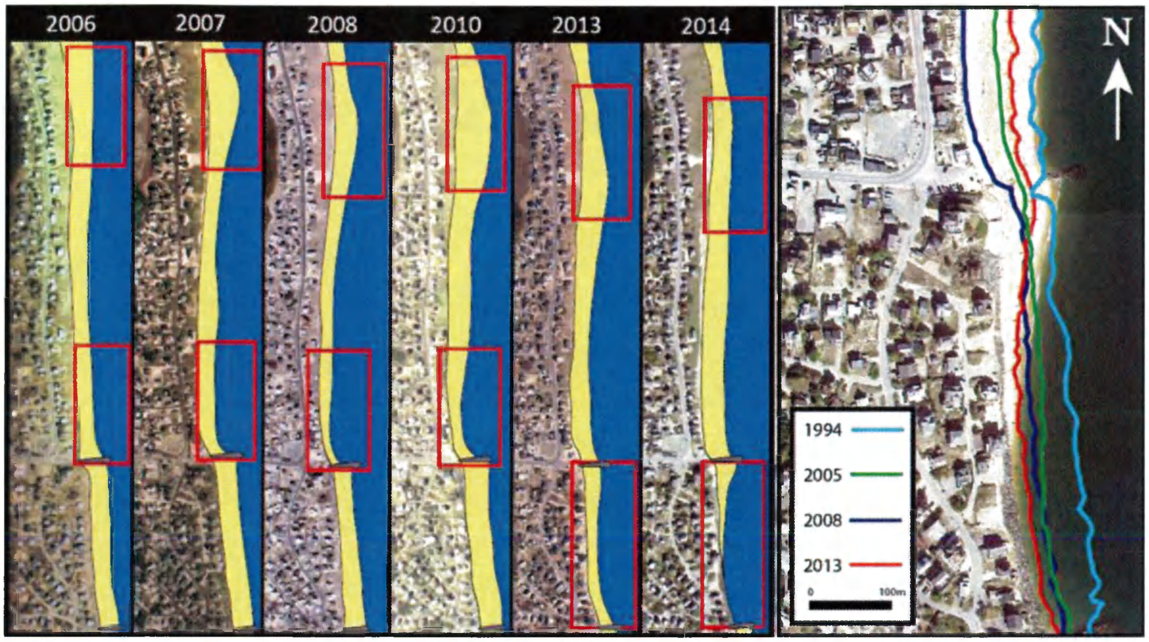

N
Legend
1928
1953
2005
2008
2013
1912, 1970,
1974, 1976,
1978, 1990,
1991, 1994
100 m
Steady-state
shoreline position

Figure 5: Center Island and Annapolis Way shoreline change from 2006 to 2014. The erosion hotspot first formed in 2007 and then migrated from Center Island to Annapolis Way. It currently (fall 2015) appears to be shifting position south once again to Fordham Way. All four shorelines are overlain on 2014 imagery.



2006
2007
2008
2010
2013
2014
N
1994
2005
2008
2013
0
100m

Figure 6: Monthly beach volumes from entire northern 2.8 km of Plum Island beach and individual sectors. Volumes are normalized by length of beach within a given sector and present average cross-shore volume changes per meter of beach. Significant wave height data is shown in grey.

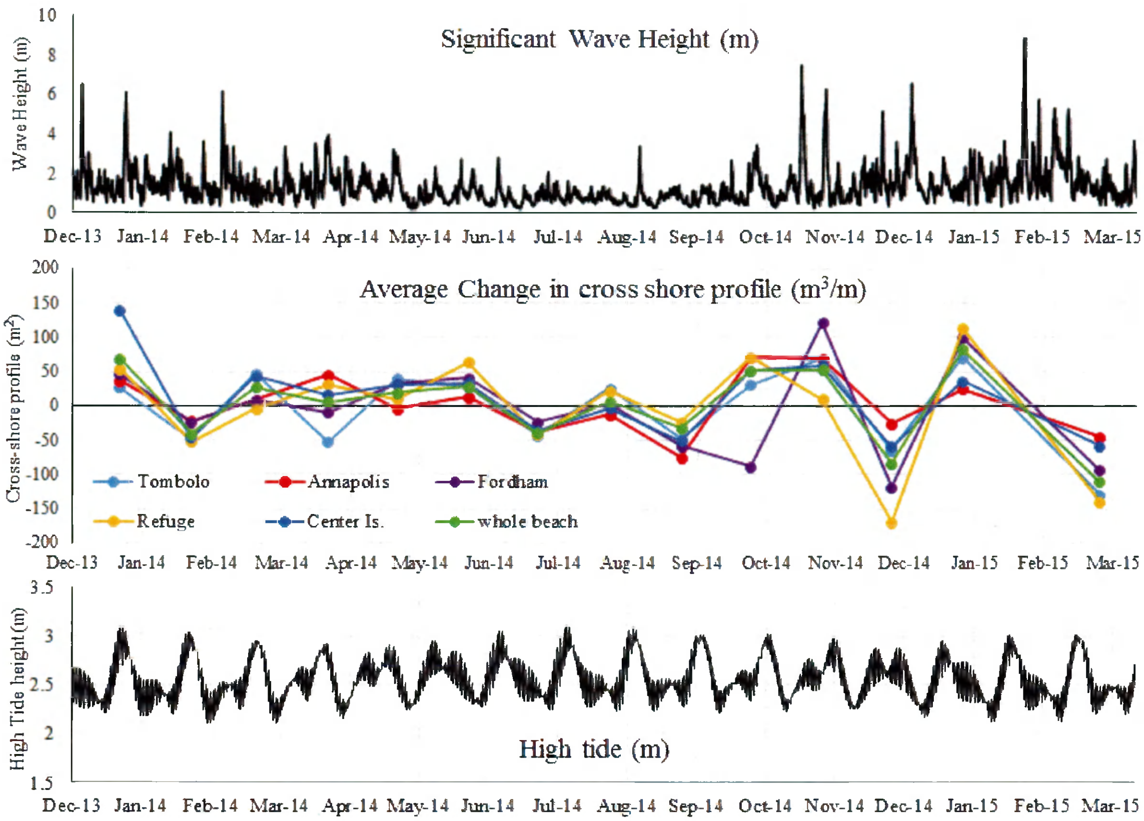

Significant Wave Height (m)
Wave Height (m)
Dec-13 Jan-14 Feb-14 Mar-14 Apr-14 May-14 Jun-14 Jul-14 Aug-14 Sep-14 Oct-14 Nov-14 Dec-14 Jan-15 Feb-15 Mar-15
Average Change in cross shore profile (m³/m)
Cross-shore profile (m²)
Tombolo
Annapolis
Fordham
Refuge
Center Is.
whole beach
High tide (m)
High Tide height (m)

Figure 7: Monthly change in beach volumes for five study sectors of northern Plum Island, normalized by volumetric change in the entire northern 2.8 km, a proxy for overall seasonal beach changes. Thus, graph demonstrates variability of any one sector of the beach from the mean beach change during a given period. Significant wave height data is shown in grey.

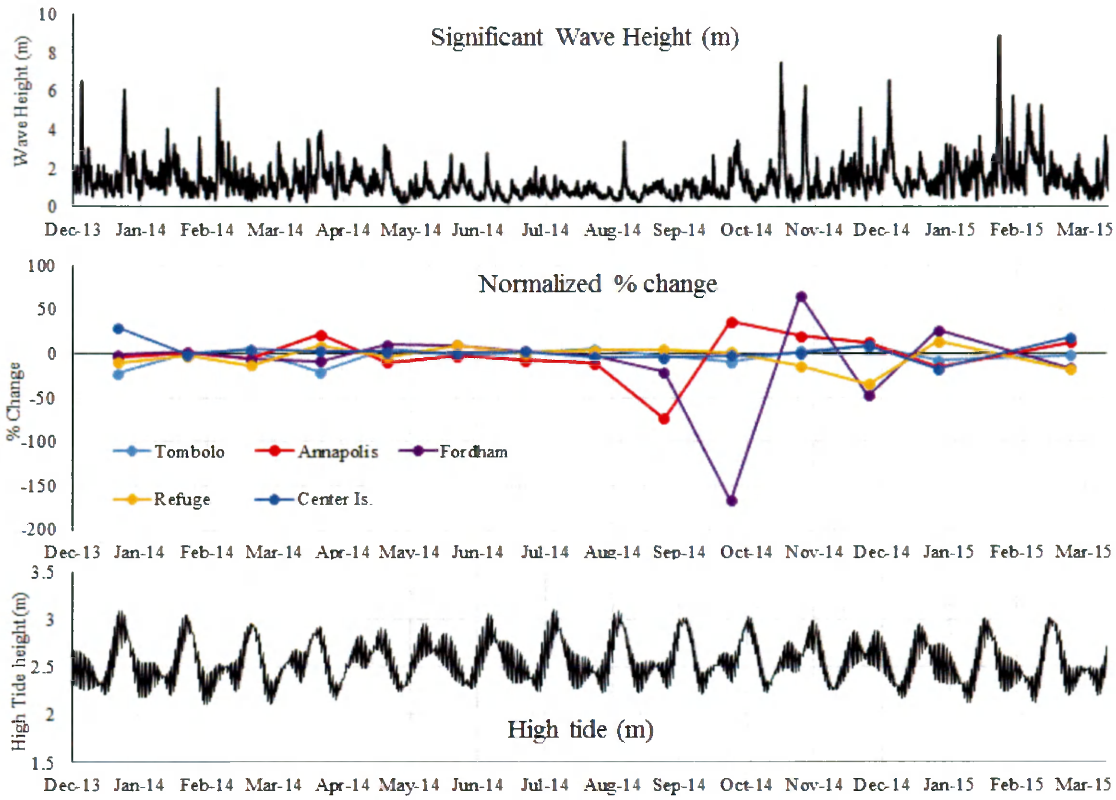

Significant Wave Height (m)
Wave Height (m)
Normalized % change
% Change
Tombolo
Annapolis
Fordham
Refuge
Center Is.
High tide (m)
High Tide height (m)
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
May-14
Jun-14
Jul-14
Aug-14
Sep-14
Oct-14
Nov-14
Dec-14
Jan-15
Feb-15
Mar-15

Figure 8: Digital topographic models of Annapolis Way and Fordham Way sections of the Plum Island beach in September 2014 and March 2015. The rip-rap revetment in the pictures was emplaced in response to erosion in 2013. Note the substantial accretion (*ca.* 30,000 m^3 of sediment) that occurred along the beach north of the Annapolis Way Groin during the intervening winter months.

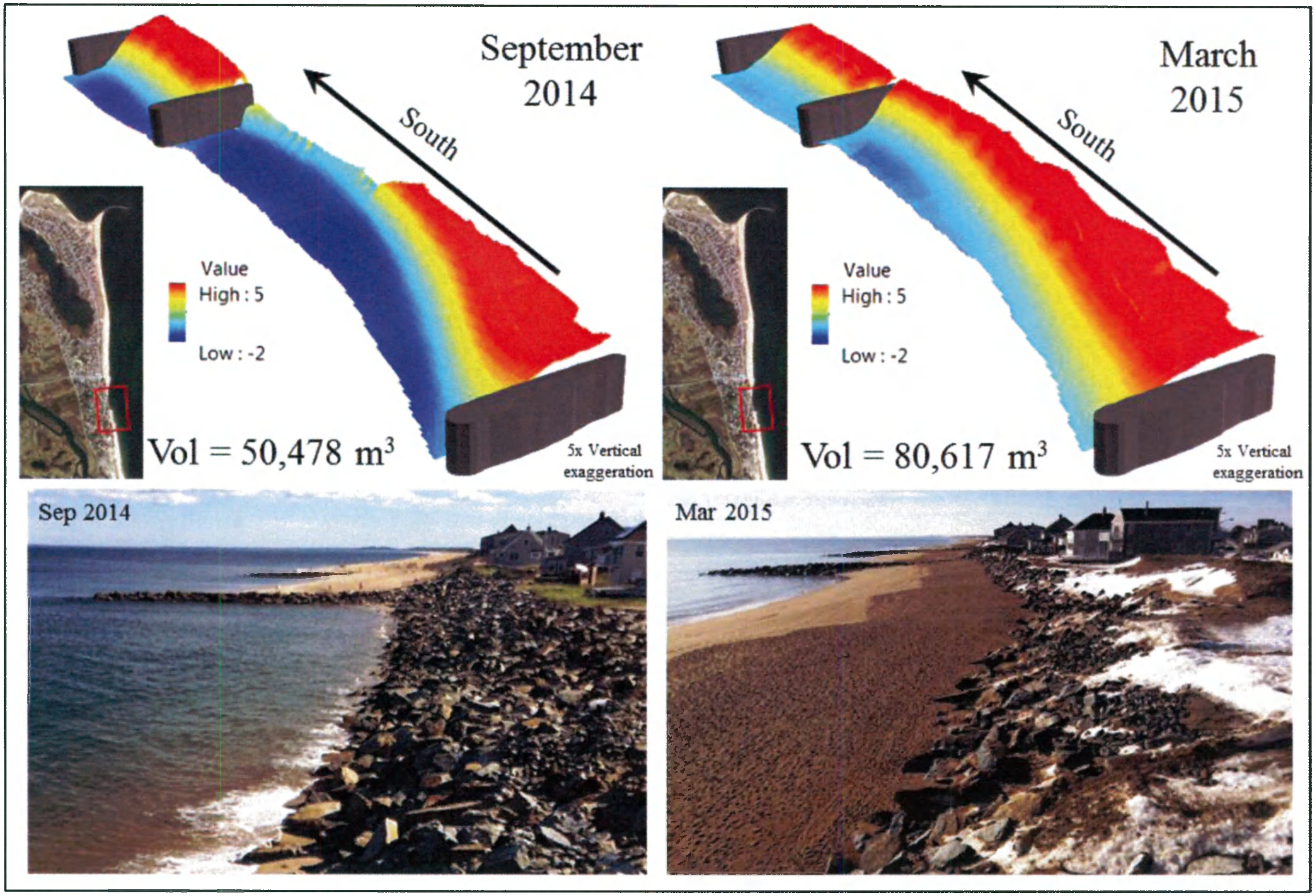

September
2014
South
Value
High : 5
Low : -2
Vol = 50,478 m³
5x Vertical
exaggeration
March
2015
South
Value
High : 5
Low : -2
Vol = 80,617 m³
5x Vertical
exaggeration
Sep 2014
Mar 2015

Figure 9: Digital topographic models of Annapolis Way and Fordham Way sections of the Plum Island beach in September 2014 and March 2015. The two profiles A-A' and B-B' are compared between September 2014 and March 2015. The profile along Annapolis Way shows large accretion during the 6 month span, while the profile along Fordham Way shows erosion over that same span.

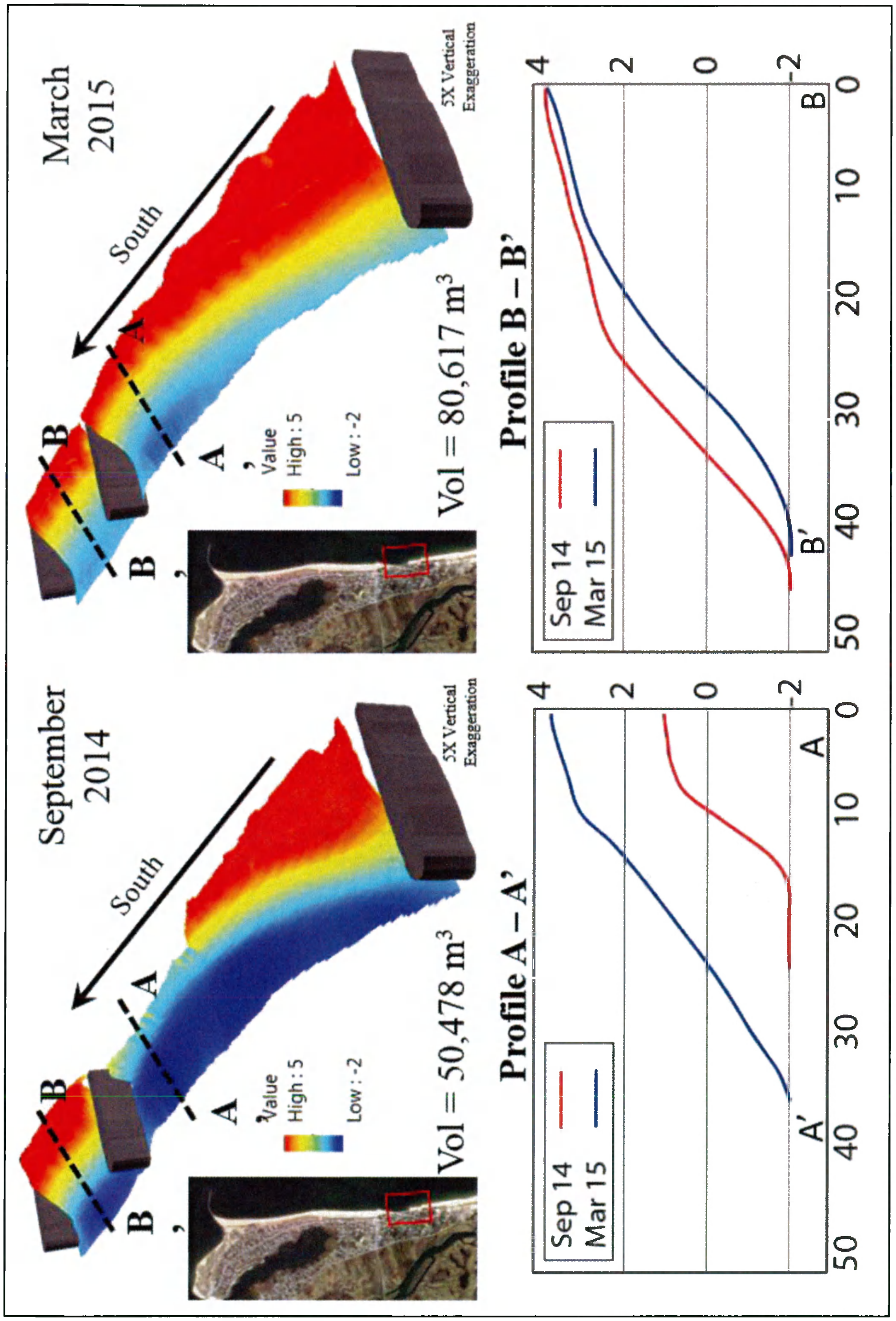

September 2014
March 2015
South
B
A
Value
High : 5
Low : -2
5X Vertical Exaggeration
Vol = 50,478 m3
Vol = 80,617 m3
Profile A – A'
Profile B – B'
Sep 14
Mar 15
A'
B'

Figure 10: Conceptual model illustrating the process of hotspot erosion as associated with elongation and migration of the ebb-tidal bar associated with the southern extent of the ebb-tidal delta, and the break-in-bar between that feature and the nearshore longshore bar which extends along Plum Island.

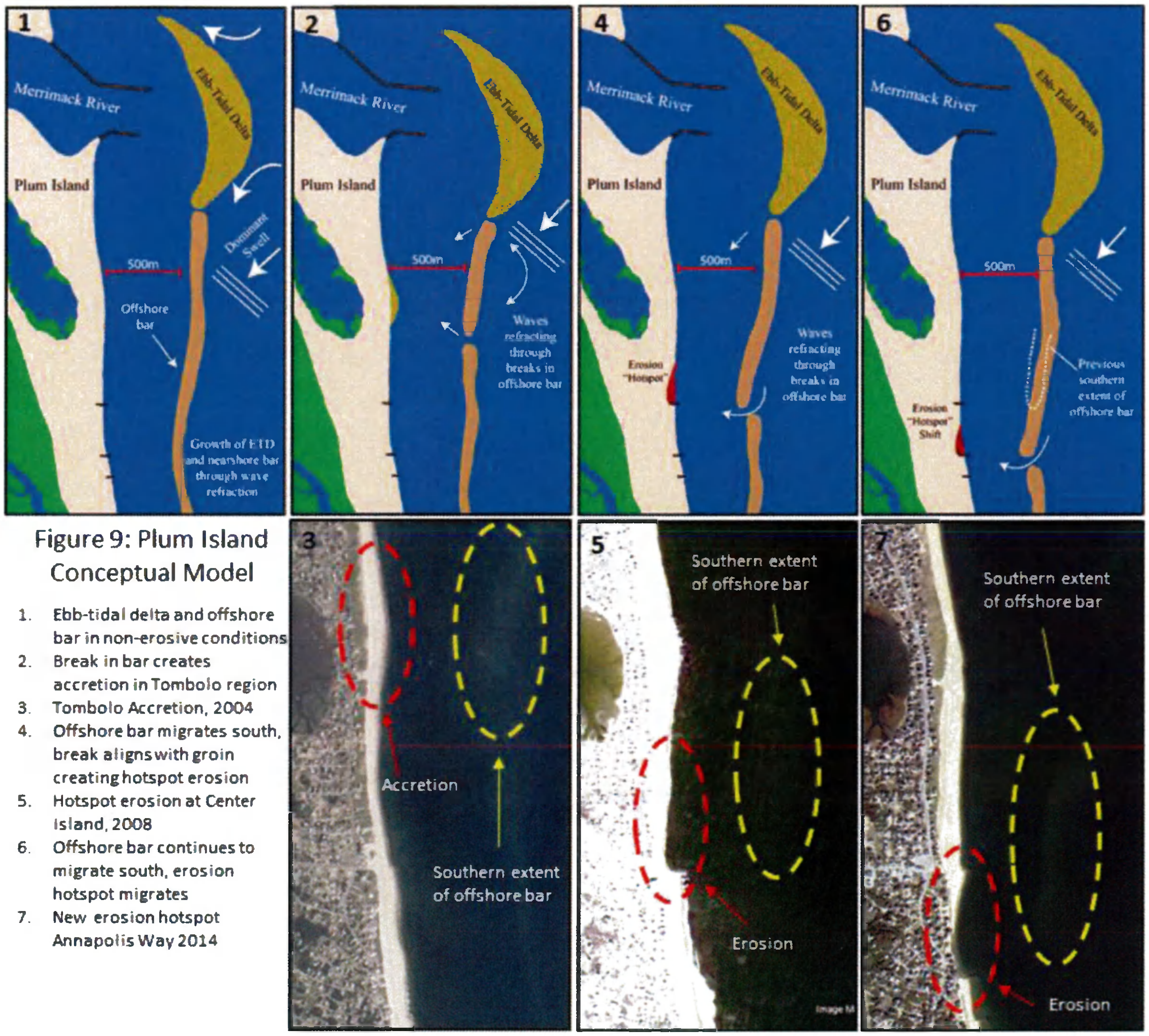


Figure 9: Plum Island Conceptual Model

1. Ebb-tidal delta and offshore bar in non-erosive conditions
2. Break in bar creates accretion in Tombolo region
3. Tombolo Accretion, 2004
4. Offshore bar migrates south, break aligns with groin creating hotspot erosion
5. Hotspot erosion at Center Island, 2008
6. Offshore bar continues to migrate south, erosion hotspot migrates
7. New erosion hotspot Annapolis Way 2014

Table 1: Literature review of impacts of tidal inlets on downdrift erosion. Review includes sites from around the world in a range of physical regimes (significant wave heights from 0.26 m up to 10 m in high surge conditions and <0.5 m – 11 m tides). The wide range in conditions provides examples of downdrift erosion due to sediment bypass dynamics for useful comparison to the 25-30 year cycles of erosion along northern Plum Island.

Cyclical shoreline erosion linked to tidal inlet processes: Literature review						
Author	Paper	Site	Physical regime	Sediment source/transport	Hard structures	Erosion patterns
Hubbard, 1979	Changes in inlet offset due to stabilization	Merrimack inlet, MA	2.7m tide, 1.2 m waves	Longshore transport to south, sediment source mainly fluvial	2 jetties, 800m & 600m, 3 groins 2 km south of inlet	Hotspot cycles of up to 100 m shore perpendicular, 30 year cycles lasting 2-10 years
Garel et al., 2014	Decadal morphological response of an ebb-tidal delta and down-drift beach to artificial breaching and inlet stabilization	Guadiana Estuary, southern Portugal	2m tide, 1 m wave	strong Longshore transport to east, sediment from both longshore and from estuary mouth	2 jetties, W. 2040m and E. 1340 m disconnected subaqueous jetty	Cycles of erosion several km E. of inlet, severe bypassing across island, >3 km. ~15 yr cycles
Galgano, 2009	Beach Erosion adjacent to stabilized microtidal inlets	Moriches Inlet, Long Island, NY	microtidal	Very strong longshore transport to the west. No significant fluvial component	2 jetties, 432 m long each	Multiple arcs of erosion, mobile move as a wave and decreasing in magnitude further from inlet.
Elias & van der Spek, 2006	Long-term morphodynamic evolution of Texel Inlet and its ebb-tidal delta (The Netherlands)	Texel Inlet, Netherlands	1.4 m tides, 1.3 m waves	Longshore transport to north. No fluvial source but pronounced flood and ebb tidal deltas as well as other barriers along the Wadden sea (only sand source)	stone revetments on Texel Island to manage inlet throat	some erosion on the down drift beach but not highly developed area, therefore not well monitored
Oertel, 1977	Geomorphic cycles in ebb deltas and related patterns of shore erosion and accretion	Sea Island section of the coastal plain physiographic province, GA	2-3m tides, ~1m waves	transport to the south, with sediment from both updrift beach and Tybee creek (small)	none	Erosion at proximal end of spit during mature ebb delta (lots of spill over channels. Erosion at distal end of inlet during youthful ETD (one channel)
Hume and Herdendorf, 1992	Factors Controlling tidal inlet characteristics on low drift coasts	NE New Zealand (study covers 16 all on north coast)	1.0-2.5m waves, 0.5-1.5m waves (depending on specific inlet and storms)	range of fluvial inputs (SMRs) and some littoral transport but in general low sediment inputs	small pairs of jetties on two inlets, primarily natural system	Relative stability of inlet position due to headland sheltering, with only subtle changes to inlet throat. No notable downdrift erosion
Robin, 2009	Short-term to decadal-scale onshore bar migration and shoreline changes in the vicinity of a mega tidal ebb delta	West Cotentin coast, central English channel, Regneville Inlet	11m average tides, typical .5 m waves, up to 2m during periods of intense storms	largely tide influenced, with massive exchange through ebb-tidal delta, extending 4 km offshore	none	Swash bar in relation to shoreline position: when 400 m offshore resulted in 80m of beach erosion. Bar welded to intertidal beach having small 15-20m erosion before eventual welding

FitzGerald, 1984	Interactions between the ebb-tidal delta and landward shoreline: Price inlet, south Carolina	Price Inlet, South Carolina	mixed energy, tide dominated, 1.5 m tides, 1.3 m waves	southern transport, primarily from updrift beaches, little if any fluvial input	none	Prime example of inlet-sediment bypassing. Short-term accretionary patterns of 4-7 years of ETD breach to onshore welding.
Hansen and Knowles, 1988	Ebb-tidal delta response to Jetty construction at three south Carolina inlets	Murrells[1], little river[2] and Charleston harbor[3] inlets, South Carolina	1.5m tides, 1.0-1.5m waves, tidal prism = 7[1], 15[2], 135[3] (values in millions of cubic meters)	Southern transport minimal fluvial input at Murels and Little River inlets, significant transport at Charleston Harbor	pair of jetties at all three sites	Reestablishment of ebb-tidal delta occurred at Charleston harbor, Murrell's and little river inlets ~5 years after jetty construction but further offshore. Welding of onshore bars was observed at all sites except Charleston Harbor
Buijsman et al., 2003	Grays Harbor, Washington Navigation Improvement project general investigation feasibility study	Grays Harbor estuary, southwest Washington	3.0-3.5 m tides, 2.1m waves, large surge reaching 10+ m	Transport S to N but still within the Columbia River littoral cell (45 miles south)	pair of jetties, 3000m & 2700m	Enormous Accretion 10-100m/yr along north and south beaches following jetty construction (1910) until ~1950 when south beach began eroding at 4 m/yr while N. beach continued to accrete at ~10m/yr
Wang and Beck, 2012	Morphodynamics of an anthropogenically altered dual-inlet system: John's Pass and Blind Pass, west-central Florida	John's and Blind Pass, west-central FL	~0.8 m tides, 0.26 m waves, mild mixed energy	Transport to the south, minimal fluvial input	pair of jetties at both passes	John's pass has significant ETD but is a largely stable system. Blind Pass is not stable, but tends to migrate south with some downdrift erosion.
Pacheco et al., 2010	Hydrodynamics of a multiple-inlet system	Ria Formosa, multiple inlet barrier system in S. Portugal	2m tides, 1 m waves	Mix of west and east transport, minimal influence of wind on circulation. Transport is dominated by periodic storms and inlet exchange	6 total inlets: 2 jettied inlets, 2 artificially relocated inlets and 2 natural inlets	Little attention to up/downdrift erosion, instead determined multiple inlet stability is possible through exchange of joint tidal prism volumes through varying spring neap cycles
Buonaiuto & Bokuniewicz, 2008	Hydrodynamic Partitioning of a Mixed Energy Tidal Inlet	Shinnecock Inlet, NY	0.88 m tides, 1-1.6m waves	Westward transport prevails with some transport reversal from hurricanes	Pair of Jetties	fluctuations in adjacent shoreline are dependent on availability of littoral transport determined by strong incident waves, altering position of migratory bars and attachment points
Fontolan et al., 2007	Sediment storage at tidal inlets in northern Adriatic lagoons: Ebb-tidal delta Morphodynamics, conservation and sand use strategies	A series of 6 inlets, Northern Adriatic coast (Italy) between the Isonzo and Po Rivers	~0.6 m tides, <0.5m, offshore storm waves up to 5 m	transport convergence area, overall but southwest transport at jettied inlet (Lido)	5/6 inlets have insignificant jetties/embankments, one is stabilized with jetties influencing sedimentation patterns	After Jetty construction (1886) Lido inlet's ETD was destroyed and still not rebuilt, dredging likely halting full ETD formation. Updrift beach has accreted at range of 15-5 m/yr.

Castelle et al., 2007	Dynamics of a wave-dominated tidal inlet and influence on adjacent beaches, Currumbin Creek, Gold Coast, Australia	Currumbin Creek, Australian gold coast	1 m tides, highly wave dominated up to 8m	no significant river input, dominant transport to the north 500,000m^3/yr	Currumbin Seawall/Groin installed connecting to nearshore headland and a second groin to fully stabilize inlet	Prior to engineering efforts, sediment bypassing in cycles of 7 yrs on average. Post structures, minimal bypassing and recirculation in the inlet producing complications with dredging but little downdrift beach erosion
Kraus, 2000	Reservoir Model of Ebb-tidal shoal evolution and sand bypassing	Ocean City Inlet, MD	Tidal prism = 2.3x10^7 m3/yr	Longshore transport to the south, 1.15-1.50 x 10^5 m^3/yr	two jetties constructed after the inlet breached in 1933	Severe downdrift erosion on Assateague Island following jetty construction. Bypassing and attachment of ebb shoals occurred over a 40+ yr period
Pope, 1991	Ebb delta and shoreline response to inlet stabilization, examples from the southeast Atlantic Coast	4 inlets, in South Carolina and Georgia (Murrells, Little, Charleston Harbor and St. Mary's)	1.4-1.8 m tides, 0.5-0.7 m waves. St Mary's tidal prism = 135 million cubic meters (other values listed above)	Southern transport, larger fluvial input at the two larger sites	1 km long jetties at Murrell's and little inlets, 6 & 7 km long jetties at Charleston Harbor and St. Mary's, respectively	Qualitative study: Ebb delta complex in any jetty complex will change shape and likely enlarge due to increased depth. This may include change to adjacent shorelines and may take years to establish a new equilibrium
Dickson et al., 2009	Coastal storms, sediment budgets, and mitigating engineering in Saco Bay	Saco Bay, ME	3.0-3.5 m tides, 1-1.5 m waves	northern longshore transport via Saco R.	Two jetties (1.4 & 1.8 km) at mouth of Saco R. 3 km of rip rap shore N. of inlet	downdrift beaches (5-6 km north) experience 2-3 years erosion/year since jetty construction (1869)

Table 2: Erosive shoreline years with corresponding location, distance to steady state shoreline and mitigation response, if any. The 1912 shoreline was taken immediately following completion of the southern jetty. The 1953 to present erosive shoreline have prompted a combination of hard and soft engineering mitigation strategies in the areas of severe erosion.

Shoreline Year	Highest Erosion Location (Fig. 1)	Erosion distance to steady state shoreline (shore perpendicular)	Mitigation response
1912	200 m north of tombolo	110 m	unknown
1928	Tombolo	100 m	unknown
1953	Right Prong	115 m	Beach nourishment 425,000 m^3, construction of four Groins
1978-79	Center Island south to Fordham Way	95 m	Intermittent rip rap revetments, notably along Fordham Way
2008-2014	Center Island south to Annapolis Way	110 m	Coir bags along Center Island; rip rap revetments along Annapolis Way

Table 3: Historic shoreline data sources used for HWL Geographic Information Systems shoreline analysis. Table shows three primary sources; National Oceanic and Atmospheric Association, United States Army Corps of Engineers and The United States Department of Agriculture. All sources mapped at 1:1,000 resolution with a minimum of 9 georeferenced control points to ensure accuracy.

Date	Source	Mapped scale	Estimated error	Georeferenc ed control points
1912	MASS GIS: National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey	1:1,000	+/- 4.3 m	9
1928	MASS GIS: National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey	1:1,000	+/- 4.3 m	9
1953	MASS GIS: National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey	1:1,000	+/- 4.3 m	9
1970	U.S. Army Corps of Engineers	1:1,000	+/- 2 m	12
1974	U.S. Army Corps of Engineers	1:1,000	+/- 2 m	12
1976	U.S. Army Corps of Engineers	1:1,000	+/- 2 m	12
1978	U.S. Army Corps of Engineers	1:1,000	+/- 2 m	12
1990	U.S. Army Corps of Engineers	1:1,000	+/- 2 m	12
1991	U.S. Army Corps of Engineers	1:1,000	+/- 2 m	12
1994	Mass GIS: US Department of Agriculture	1:1,000	+/- 1 m	15
2005	Mass GIS: US Department of Agriculture	1:1,000	+/- 1 m	15
2008	Mass GIS: US Department of Agriculture	1:1,000	+/- 1 m	15
2013	Mass GIS: US Department of Agriculture	1:1,000	+/- 1 m	15

Table 4: Sediment volumes (m^3) for 13 survey months, whole beach and subsections. Sediment volumes were created through ArcScene 10.1 kriging interpolation. The subsection volumes were subsampled from the whole beach volumes using the same shapefile clip to make sure each subsection is the same for every survey period.

Date	whole beach	Tombolo	Annapolis	Fordham	Refuge	Center I.
Dec-13	605049	155865	45917	20336	123723	65400
Jan-14	803167	168762	59004	26788	149655	123524
Feb-14	687027	144720	51021	23477	124419	104546
Mar-14	763284	167804	54135	24627	122457	122446
Apr-14	779934	142255	70469	23210	137230	129127
May-14	837010	161583	68835	27691	142044	142178
Jun-14	915673	175651	73482	33484	172366	156104
Jul-14	802657	154877	59746	30173	152094	140902
Aug-14	821738	167631	55156	30446	162607	139638
Sep-14	728371	144721	28084	22394	151109	118500
Oct-14	877215	159714	53619	10111	185020	140146
Nov-14	1027626	193008	78461	34629	189530	164847
Dec-14	788012	161739	69111	18029	108016	140455
Jan-15	1025259	196130	77896	31981	162314	155578
Mar-15	708563	133412	61714	18903	95123	131586

Table 5 Sediment volume (m^3) changes from month to month, whole beach and subsections. This table shows the fluctuation from each survey period to another. The focus of this table is to highlight large swings in sediment volume from one month to the next, either position (accretion) or negative (erosion).

Date	whole	Tombolo	Annapolis	Fordham	Refuge	Center Is.
Jan-14	198118	12897	13087	6452	25932	58124
Feb-14	-116140	-24042	-7983	-3311	-25236	-18978
Mar-14	76257	23084	3114	1150	-1962	17900
Apr-14	16650	-25549	16334	-1417	14773	6681
May-14	57076	19328	-1634	4481	4814	13051
Jun-14	78663	14068	4647	5793	30322	13926
Jul-14	-113016	-20774	-13736	-3311	-20272	-15202
Aug-14	19081	12754	-4590	273	10513	-1264
Sep-14	-93367	-22910	-27072	-8052	-11498	-21138
Oct-14	148844	14993	25535	-12283	33911	21646
Nov-14	150411	33294	24842	24518	4510	24701
Dec-14	-239614	-31269	-9350	-16600	-81514	-24392
Jan-15	237247	34391	8785	13952	54298	15123
Mar-15	-316696	-62718	-16182	-13078	-67191	-23992
Average	7393	-1603	1128	-102	-2042	4727

Table 6: Compilation table of personal observations during beach survey periods as well as distance measurements from the recent satellite imagery. Observations and measurements are specifically describing the offshore bar along northern Plum Island. Personal observations of the bar were not recorded in months where the weather interfered with any visibility of the offshore bar. The satellite imagery is the same imagery found in Table 2.

Time (observation or satellite)	Observation	Location Alongshore	Distance offshore (estimated or in satellite record)
September 2006 (satellite)	Large offshore bar along southern Tombolo area	Southern extent of large bar is 300 m North of center island groin	Southern extent, 350 m
April 2008 (satellite)	Bar not very visible, poor satellite exposure	Southern extent at Center Island groin	Southern extent, 300 m
June 2010 (satellite)	Small bar visible offshore	Southern extent at 30 m south of Center Island Groin	Southern extent, 320 m
November 2011 (satellite)	Large bar complex, some subaerially in imagery	Tombolo to Center Island groin (southern extent 30 m South of groin)	Southern extent, 240 m
August 2013 (satellite)	Major break in bar at southern extent, with minor swash bars to the north	150 m North of Annapolis Way Groin	Southern extent, 300 m
Dec 2013 (observation)	Waves crashing along bar at low tide	Center Island	~400 m
Jan 2014 (observation)	Overcast		
Feb 2014 (observation)	Overcast		
Mar 2014 (observation)	Waves crashing over bar at low tide	tombolo	~400 m
April 2014 (observation)	Birds hovering over bar, very calm but still waves crashing	Tombolo to northern Annapolis Way	
May 2014 (observation)	Large waves at low tide	Tombolo to northern Annapolis Way	
June 2014 (observation)	Waves and bar visible at low tide	Center Island to Annapolis Way	~300 m
July 2014 (observation)	Small waves and birds hovering along bar	Center Island to Annapolis Way	
August 2014 (observation)	Calm, no waves, birds clustered along bar	Center Island to Annapolis Way	
September 2014 (observation)	Waves at low tide	Center Island to Annapolis Way	
October 2014 (satellite & obs)	Waves and birds at low tide	50m North of Annapolis Way groin	Southern extent, 240 m offshore
November 2014 (observation)	Calm, no waves but birds along bar	Center Island	
December 2014 (observation)	Overcast		
January 2015 (observation)	~1m waves breaking along bar at low tide	Center Island to Annapolis Way	~300 m
March 2015 (observation)	Calm, intermittent small waves at low tide	Tombolo to Annapolis Way	

Chapter 2:

Evaluating the impact of beach erosion, shoreline protection and piling construction on the housing market

Abstract

Coasts around the world are facing enhanced erosion resulting from accelerated sea-level rise, increased storminess and a decrease in sediment supply. Widespread development in coastal areas puts enormous pressure on policy makers due to the financial investment in coastal infrastructure from both governments and homeowners. Here, we investigate the environmental factors which contribute to the value of coastal homes on Plum Island, a partially developed barrier island in the western Gulf of Maine. Specifically, we utilize a hedonic regression model to determine the contributing value of shoreline protection and raised piling construction. On average, home is $20,000 more valuable with some kind of private protection structure and $70,000 more valuable if protected by a public structure. Similarly, a house built on raised pilings is worth on average $20,000 more than a house with a traditional foundation. The insignificance of home values to a time-to-inundation variable reflects the impact of complex 25–30-year cycles of shoreline erosion and accretion dominating change along this particular beach. This approach can be used as a tool for both characterizing the economic risk of erosion to coastal communities as well as determining the role of shoreline-change patterns unique to a particular site in driving the local housing market.

Introduction

Worldwide, coastal communities are increasingly becoming impacted by rapid shoreline changes associated with rising sea level, increasing storminess, and decreasing sediment supply (Donnelly *et al.* 2004). In the United States, due to the impacts of dams, deforestation, and urbanization, fluvial sediment export to the coast today is only about 80 percent of what was available prior to European settlement (Syvitski *et al.* 2005). This sediment deficit is amplified by relative sea-level rise, which is occurring at up to 0.15 mm/yr in some places along the US east coast (Kensington and Han 2014).

In the United States, shoreward migration has been the most pronounced on barrier islands, where more than 75 percent of barriers experience some form of erosion (Pilkey and Thieler 1992). As a consequence, coastal communities experience regular inundations from flooding and storm surges, and erosion can lead to extensive losses for property owners. Twenty-five percent of property owners within 150 m of the shoreline may be affected by property losses due to erosion over the next 50 years (Kriesel *et al.* 2000).

These physical effects of coastal erosion imply a likelihood of significant economic impacts. In order to mitigate potential impacts, coastal communities have a stake in identifying strategies for sustainable adaptation to shoreline changes. Adaptive strategies include: soft stabilization and beach replenishment; hard stabilization with jetties, groins, or revetments; structural modifications, such as elevating a residence on pilings; or the abandonment of coastal properties. All of these strategies involve significant economic costs, which are relatively straightforward to estimate; evaluating the economic benefits of these strategies can be much more difficult, however. In this paper, using data from a coastal housing market, we apply the hedonic pricing method (HPM) to develop estimates of the relative benefits to property owners of alternative strategies for mitigating the adverse effects of shoreline changes on coastal properties.

Study site: Plum Island, Massachusetts

Plum Island, the longest barrier island in the Gulf of Maine, is located on the northeast coast of Massachusetts (Fig. 11). It is backed by the largest marsh system in the US north of Long Island, NY, the "Great Marsh". At the northern end of the island is the mouth of the Merrimack River and its associated tidal inlet. Plum Island is rare among US east coast barrier islands in that it is not undergoing landward migration. The geologic features of this coastal barrier are distinctive because, although severe, short-term erosion can occur locally, and on a longer, decadal scale, Plum Island comprises a stable shoreline (see Chapter 1 of this thesis). Over the last 150 years, taken as an aggregate, Plum Island has experienced long-term erosion at the statistically insignificant rate of 0.3 ± 2.9 ft/yr (Thieler *et al.* 2013). This observation complicates the most appropriate way for coastal property owners to respond to short-term shoreline changes.

Plum Island and the coastal region surrounding the Great Marsh were settled originally by Europeans in the late 17th century. Through the 18th and 19th centuries, the Great Marsh was mowed for salt hay and used as a grazing area for livestock (Waters 1905). By the 19th century, the town of Newburyport had become a commercially viable port on the Merrimack River (Labaree 1962), but Plum Island remained uninhabited. In

1806, the Plum Island Turnpike Bridge Corporation was established with the goal of creating a summer vacation destination on Plum Island (Fig. 12). The Corporation constructed the first bridge connecting Plum Island to the mainland (later Plum Island Turnpike) and built the Plum Island Hotel, the only permanent structure on Plum Island for decades (Currier 1919). Plum Island did not develop many permanent structures until 1920 when the Plum Island Beach Company bought all land north of the turnpike and subdivided 1,400 acres into 12,000 lots (McDonnell 1920).

At the mouth of the Merrimack is a highly dynamic tidal inlet. Over historic time, the inlet and northern section of the barrier island have undergone periods of river mouth migration, causing large shifts in Plum Island's location relative to today (FitzGerald 1993; Hein *et al.* in review). Historically, these geological processes posed serious navigational challenges for upstream commercial ports, leading eventually to the construction of a jetty at the river mouth by 1914. Following jetty construction, the northern portion of Plum Island experienced successive cycles of small-scale shifts (~80–100 m) in shoreline position, driven by the formation and alongshore migration of an erosion hotspot associated with complex wave dynamics and inlet sediment transport processes; this resulted in periods of alternating erosion and accretion along the northern 3 km of Plum Island (see Chapter 1 of this thesis). In response, a variety of mitigation strategies were employed to protect public and private properties, with varying degrees of success. These strategies included the construction in the 1960s of a series of groins, set perpendicular to a 500-m long stretch of the beach and, more recently, dune stabilization measures, such as sand-filled coir bags and rip-rap revetments.

In the last ten years, episodes of extreme, but localized, erosion have prompted federal, state, and local governments to pay particularly close attention to Plum Island. While significant private and public properties and infrastructure have been preserved, more than a dozen properties have been lost to erosion over the past seven years (Schworm 2013). Because of the numerous stakeholders, the potential risks of residential losses, and the construction of seawalls or other protective structures, Plum Island is a fitting location for analyzing the potential benefits of shoreline protection.

Hedonic pricing models as a tool for economic analysis

Hedonic pricing models have been utilized for more than 40 years as a way to estimate the implicit prices of the individual attributes of multidimensional goods, including non-market attributes (Berry and Bednarz 1975). These models have been used with increasing frequency to estimate the costs associated with coastal hazards, such as inundation and erosion (Kriesel and Lichtkoppler 1993; Kriesel *et al.* 2000; Eberbach and Hoagland 2010; Au 2011; Jin *et al.* 2015) in different locations nationwide (Fig. 3). A comparison of coastal hedonic studies and environmental variable significance is presented in Table 7.

Kriesel *et al.* (2000) conducted one of the most comprehensive and geographically wide-ranging analyses of the economic risks of coastal erosion. The model developed by these authors examined four different US regions (the Atlantic, the Gulf of Mexico, the Great Lakes, and the Pacific). The authors argued that the estimated implicit prices of the model predictors could be interpreted as exact measures of economic welfare changes (*cf.*, Kriesel *et al.* 1993) because the marginal implicit price is approximately equal to the owner's marginal willingness to pay, as shown by Smith (1985). Consequently, because actions taken by property owners to protect their residences from flooding and erosion help to prolong the survival of their properties, the estimated implicit prices of such actions, as manifested in property attributes, comprise measures of their economic benefits.

Methods

Freeman (1993) presented a hedonic model in which the price of housing (*P*) is determined by attributes that fall into three general categories (eq. 1):

$$P = f\,(\boldsymbol{S}, \boldsymbol{N}, \boldsymbol{E}) \tag{1}$$

In this model, the three general categories comprise structural (***S***), neighborhood (***N***), and environmental (***E***) attributes. The structural variables are standard attributes that describe a residential property, including lot size, number of bedrooms, number of bathrooms, house age, among others. Neighborhood characteristics include the identity of a municipality and the distance to a central business district. Environmental variables include distance to the shoreline — sometimes referred to as an "erosion feature" — elevation, and a variable denoting the number of years until a property becomes inundated, given that property's location (*e.g.,* distance from the shoreline) and the proximal shoreline erosion rate (Kriesel *et al.* 2003), which the authors label "geotime."

The hedonic model that we develop here for Plum Island follows the approach taken by Jin *et al.* (2015). The main goal is to estimate the net benefits (or costs) of geologic hazards, environmental attributes, and mitigation structures.

The structural variables for this study were compiled from Town Assessors' data from the towns of Newbury and Newburyport, Massachusetts. Data sources for the environmental variables at each property are derived from MassGIS, Lidar, FEMA, and personal observations (Fig. 14). We employ a categorical neighborhood variable that denotes whether a property is located in the town of Newbury (0) or Newburyport (1). Table 8 presents a full list of variables included in the model with descriptive statistics. Some variables are continuous, such as lot size or distance to shore. Other variables are categorical (0,1 or "dummy" variables), such as beachfront location or piling construction.

We estimate the model with ordinary linear regression (eq. 2):

$$\ln(P_i) = \beta_0 + \boldsymbol{\beta_1}\mathbf{S}_i + \boldsymbol{\beta_3}\mathbf{N}_i + \boldsymbol{\beta_2}\mathbf{E}_i + \varepsilon_i \qquad (2)$$

Where $\ln(P_i)$ is the natural logarithm of the assessed value of property *I*; the $\boldsymbol{\beta}$'s are vectors of parameters to be estimated for housing attributes in each general category.

The estimated model parameters comprise percentage changes in a property price with changes in the relevant predictor. Once the model is estimated, we investigate changes in the expected value of a property with changes in each of the predictors, holding the values of other predictors at their means.

Results

Significant structural variables include several different housing styles and the square of lot size (Table 3). Significant environmental variables include short- and long-term erosion rates, elevations, and distances from shorelines for basin-, beach-, and backbarrier-fronting properties. Table 4 shows the cost of an average property and the 95 percent confidence interval for each significant binary variable. The environmental variables of particular interest and significance are discussed further below.

The economic importance of shoreline protection is determined through its impact on housing prices on Plum Island, both with and without protective structures. The average property is evaluated at a range of distances from the shore to highlight the influence of proximity to such structures. We considered three different types of shoreline protection: no protection, a *privately* built and maintained structure, and a *publicly* built and maintained structure (Fig. 15). For the average Plum Island property, a private structure adds about \$20,000 to its value and a public structure adds about \$70,000.

Coastal properties located on a dune in Massachusetts are subject to its Wetlands Protection Act, which is implemented through bylaws at the municipal level, and administered by local Conservation Commissions. One of the most important coastal regulations requires that new or expanded commercial and residential structures must be elevated on pilings (Klein and Freed 1989). Fig. 16 shows the estimated added value to properties that are elevated on pilings. The estimated difference between piling construction and a traditional foundation is approximately \$30,000.

All properties on Plum Island are in FEMA designated flood zones; V-, AE-, and AO-zones were included in our model. Flood zone V comprises lands that have a one percent risk of flooding and are susceptible to high wave velocity; flood zone AE comprises lands that have a one percent risk of flooding; and flood zone AO comprises lands that have a one percent chance of shallow flooding, all with respect to the 100-year flood. The V-zone was the only zone found to be significant, a property in the V-zone is worth about $10,000 more than the average home on Plum Island.

We examined the effects of two shoreline change rates: a 30-year short-term record and a 125-year, long-term record. The two shoreline change rates were determined for Plum Island by the US Geological Survey and the Massachusetts Office of Coastal Zone Management (Hapke *et al.*, 2011). Estimating the model with two shoreline change rates allows us to analyze housing prices in northern Plum Island both in respect to recent localized erosion and in light of the longer term trend towards shoreline stability (erosion rate: 0.3 ± 2.9 ft/yr; Thieler *et al.* 2013). These differences reflect that although there are instances of localized erosion, the Plum Island shoreline has been stable for the last 125 years. Furthermore, these time windows illustrate the importance of dynamic shoreline change, where erosion often can be only an ephemeral feature to an otherwise healthy beach.

In our model, both the short- and long-term erosion rates are significant variables, although the long- and short-term average change rates are 0.3 ft/yr (accretion) and -0.6 ft/yr (erosion). The long term accretion rate is more significant ($p < .0001$) than the short-term rate ($p = .0318$) likely due to a larger range of values for the short-term erosion rates

(Table 9). In contrast to the shoreline averages, however, the short-term rate (erosion, on average) has a positive influence and the long-term rate (accretion, on average) has a negative influence on property values (Table 9).

The geotime variable is calculated as shown below:

Geotime (yr) = shoreline change rate (ft/yr) / distance to shoreline (ft)

Geotime is a calculated time-to-inundation of the structure on a coastal property from shoreline erosion. Due to its dynamic nature, the time-to-inundation on Plum Island is non-uniform across properties. Further, some properties exhibit a positive geotime, indicating a finite time-to-inundation, while others have a negative geotime, suggesting an infinite lifetime. When analyzing all properties together, these contrasting results from bi-directional shoreline change cause geotime to be insignificant in the regression model.

To further investigate geotime, we divided the 1043 properties included in the model into four categories based on shoreline change rates; short-term erosion (726), long-term erosion (668), short-term accretion (317), and long-term accretion (375). When performing model runs on the two erosion sub-datasets, the geotime variable was still insignificant, suggesting that erosion risk was not incorporated into prices in the housing market.

Discussion

Table 3 lists descriptive statistical data for significant variables on Plum Island. Certain structural variables have unexpected significance. The variable denoting residence in Newbury shows that it is preferable to live there. This result could be due to the large percentage of waterfront properties in Newbury as a consequence of the shape of the island (Fig. 14). Many of the specific housing styles (bungalow, camp, conventional family, old style, and ranch) were significant, but relatively lower than the baseline. Contemporary style properties were the only style that positively impacted the property price, suggesting that property owners prefer that building style over typical beach cottages (Table 10). Dummy variables denoting waterfront views, beach, backbarrier and basin, were expectedly significant because of the high amenity value property owners place on water views and water access. Building upon the model outputs, we have highlighted several interesting environmental variables that proved to be highly significant: shoreline protection, raised piling construction, and both the short- and long-term erosion rates.

The results provide two key findings about the perception of shoreline protection on Plum Island. The first conclusion is that any form of protection is valued higher than no protection at all. The financial increase from shoreline protection is a range of $20,000 to $70,000 for private and public protection, respectively, compared to properties without protection. This result indicates that property owners put a premium on being behind some kind of artificial structure. These structures likely provide a sense of safety and security from storm surge and flooding. This perception could be short-sighted because typically the emplacement of shoreline protection structures indicates an area that previously had been eroding or had experienced inundation. The fact that this has happened in the past means it could happen in the foreseeable future, with or without a structure in place. This result is consistent with our finding of significance for the V-zone (high-velocity, wave run-up risk), reflecting the risk of flooding for properties only on the beachfront side of the island, which is the only area where properties were lost over the last seven years. A property in the V-zone is worth about $10,000 more than the average property. The increased value is likely due to an insurance premium that these property-owners pay to live in the V-zone, therefore providing a sense of security, similar to living behind a protection structure, even though there is an increased risk flooding from storm surge.

A second conclusion is that there are differences in premiums among the types of shoreline protection. Public structures are a larger scale than private structures, and, in the case of Plum Island, they consist of three groins and a terminal jetty at the northern end. Private structures include jute sand bags and rock revetments. The model predicts an increase of $70,000 over no shoreline protection and an increase of $50,000 over private structures. The premium put on public protection may relate to the perceived security of large-scale, government-funded shoreline protection projects. Further, a public structure would be maintained by an external party, implying that the costs of protection would be covered mostly by outside parties. From a geological perspective, however, the presumed protective features of a public structure might not in fact exist. The jetties and groins are designed to alter sediment transport pathways, significantly influencing localized erosion and accretion. Although a property might be located immediately adjacent to and landward of a groin, depending upon short-term sediment dynamics, that location could be a (temporary) area of very high erosion. A property owner might feel secure due to the proximity of a large public structure, but a lack of knowledge about beach morphology could leave the owner more exposed than a property without any structures shoreward of it.

The construction of waterfront and nearshore properties with elevated pilings has become more common across the United States. In Massachusetts, formal implementation of a policy for elevating properties began in 1990, depending upon municipal regulations (Klein and Freed 1989). The residential portion of Plum Island is split between Newbury and Newburyport, with Newbury having stricter regulations concerning the placement of residential structures on pilings. The use of construction pilings is beneficial during flooding and surge events, allowing the free flow of flood waters through a property, both to decrease hydraulic force and to minimize structural damage. The construction regulations rely upon FEMA flood zone maps, highlighting variable levels of risk and the corresponding building practices.

The elevated pilings variable is a categorical variable; in our assessment of elevated pilings, it is compared to properties with no piling construction at a range of distances from the shoreline. At similar distances to the shore, the difference between the assessed values of a property with pilings compared to one without is about $30,000. This economic premium for elevated pilings is a strong indicator of the significance that pilings have on coastal structures and future longevity. The free flow area among pilings makes for a much safer property construction in a flood zone and clearly warrants the premium price that property owners place on elevated pilings.

The significance of both the short- and long-term erosion rates was unexpected (Table 9), particularly because of the counter-intuitive impact on property values (negative for the more accreting long-term rate, positive for the more eroding short-term rate). These results imply that residents on Plum Island do not understand that there is a short-term (30-year) risk of property damage or loss from erosion. In turn, the significance of the long-term change rate implies that, over an extended time period (125 years), homeowners recognize a risk in a property losing value from erosion. The reason for this could be that property owners recognize erosion risk only over long time scales (>30 years) and that, otherwise, erosion is seen as a temporary process. This finding is opposite to those found from geological studies of the Plum Island beach (Hubbard 1977; Chapter 1 of this thesis), which indicate temporary periods of erosion that impact a small area, but, over decadal scales, the persistence of a relatively stable and healthy beach. The recognition of the temporal difference in risk for this model may not be entirely correct geologically, but is an indication of its use for recognizing complex shoreline change patterns and potentially could allow for characterization of a site with more uniform shoreline change.

The geotime variable (erosion rate/distance to shore) was not significant in any version of our model. There are several reasons for this result. Most importantly, complex erosion/accretion patterns drive bidirectional shoreline change along the northern 3 km of Plum Island. In addition, embodied in the geotime variable is an assumption that property owners understand coastal erosion and the associated risks (Kriesel *et al* 2000). Without this understanding, properties only increase in value the closer they are to the shore without any negative influence that could be derived from the associated erosion and flooding of shorefront living.

Conclusions

We found that shoreline protection structures and elevated piling construction are perceived as valuable in the market for coastal residences on Plum Island. Similar to other models that analyzed the economic aspects of shoreline change, we also found that property values decreased with distance from the shoreline. The dynamic nature of inlet-beach interactions along the Plum Island coastline leads to short-term cycles of erosion and accretion, the locations of which may shift over time, thereby making it problematic to estimate the costs associated with the risks of coastal erosion. This issue is manifest in the insignificance of geotime and the contrasting long- and short-term shoreline change impacts on property values.

Public protection structures, including groins and jetties, are valuable to property owners, however. This value implies that there is a perception of lowered erosion risks associated with large-scale public projects designed to prevent shoreline erosion. The costs of these projects also are shared more broadly with the public, so that the protected properties bear only a fraction of the costs of construction, maintenance, and repair. These perceptions of lower risks may be misguided, however, as both groins and jetties may cause sediment transport patterns to be disrupted in the short-term, thereby increasing risks to the longevity of waterfront residences that are not fully recognized by property owners.

Plum Island provides an excellent example of the complex interactions of dynamic shorelines and coastal development. The long-term stability of Plum Island has been overlooked recently, as the public, abetted by myopic media attention, tends to focus on the short-term impacts of infrequent northeast storms to only a small number of residences. Our model shows that the overall housing market on Plum Island is unaffected by these events, thereby reflecting its geologically stable nature. Similar models could be used in other locations facing shoreline change as a method of analyzing the financial risks to property owners and assessing the long term severity of erosion and shoreline change.

Fig. 11: Study site Plum Island, Massachusetts. 17 km long barrier island in Northern Massachusetts. Inset highlights six subsections of interest; Right Prong, “Tombolo”, Center Island, Annapolis Way, Fordham Way and Refuge.

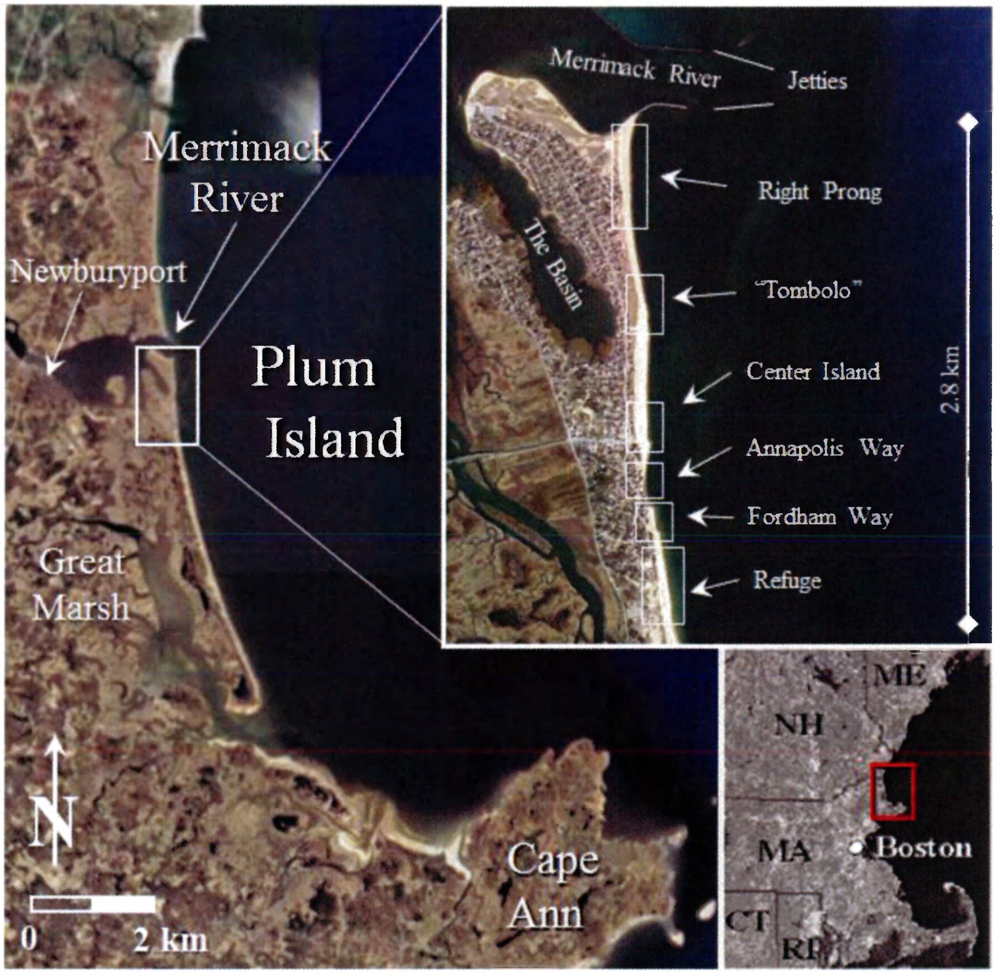
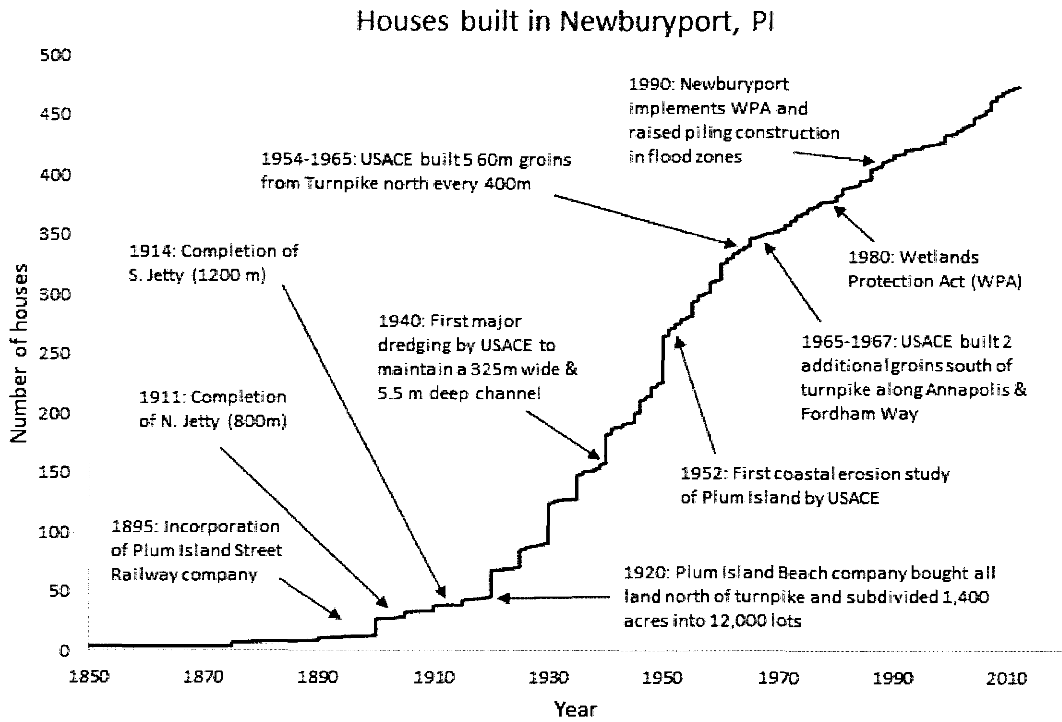
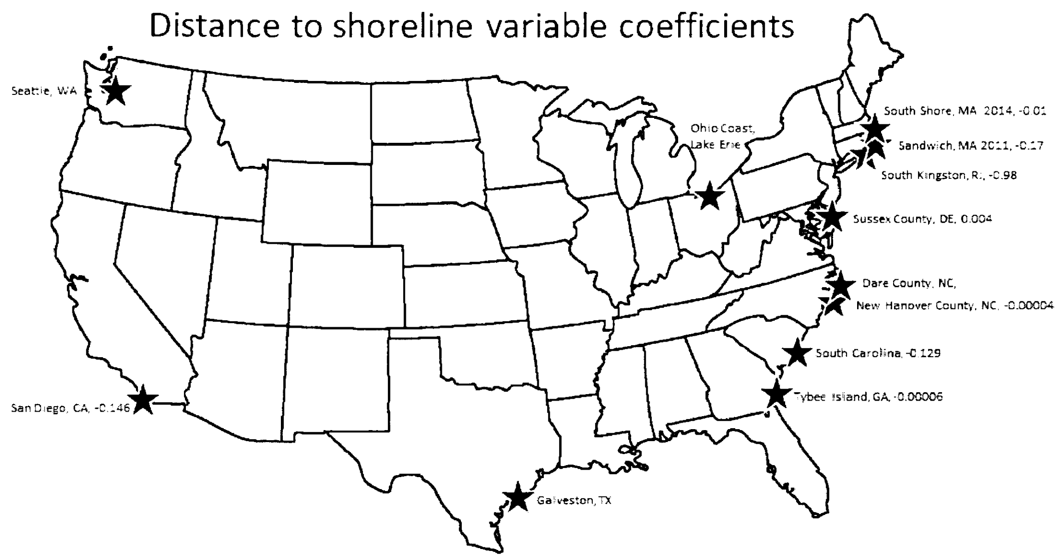

Merrimack River
Newburyport
Plum Island
Great Marsh
Cape Ann
N
0
2 km
Merrimack River
Jetties
Right Prong
"Tombolo"
Center Island
Annapolis Way
Fordham Way
Refuge
The Basin
2.8 km
ME
NH
MA
Boston
CT
RI

Figure 12: Timeline of development of Newburyport section of Plum Island. The growth in Newburyport began in 1895 with the construction of the turnpike by the street railway company. In 1920 the Plum Island turnpike bought the land north of the turnpike, which began the rapid growth of Plum Island until the 1970s when growth slowed from ~300 homes in 50 years to <150 homes in 40 years.



Houses built in Newburyport, PI
Number of houses
Year
0
50
100
150
200
250
300
350
400
450
500
1850
1870
1890
1910
1930
1950
1970
1990
2010
1895: Incorporation of Plum Island Street Railway company
1911: Completion of N. Jetty (800m)
1914: Completion of S. Jetty (1200 m)
1920: Plum Island Beach company bought all land north of turnpike and subdivided 1,400 acres into 12,000 lots
1940: First major dredging by USACE to maintain a 325m wide & 5.5 m deep channel
1952: First coastal erosion study of Plum Island by USACE
1954-1965: USACE built 5 60m groins from Turnpike north every 400m
1965-1967: USACE built 2 additional groins south of turnpike along Annapolis & Fordham Way
1980: Wetlands Protection Act (WPA)
1990: Newburyport implements WPA and raised piling construction in flood zones

Figure 13: Coastal Hedonic Pricing Model Study Site Locations. Map shows the geographic distribution of study sites around the United States to highlight the range in distance to shoreline model coefficients. Negative coefficients indicate a decrease in value with distance to shore, and the larger the magnitude the larger the decrease in value per unit of distance.



Note: Kriesel et. al, 2000 results, -.009 for 6 SE counties and -.045 for 3 Pacific counties

Fig. 14: Locations of homes (green circles) and seawalls (red lines) in northern Plum Island. Thin black lines show locations of shore-perpendicular transects evaluated for the impact of shoreline erosion on housing values. The diagonal black line bisecting northern Plum Island is the political boundary between the towns of Newburyport (north) and Newbury (south).

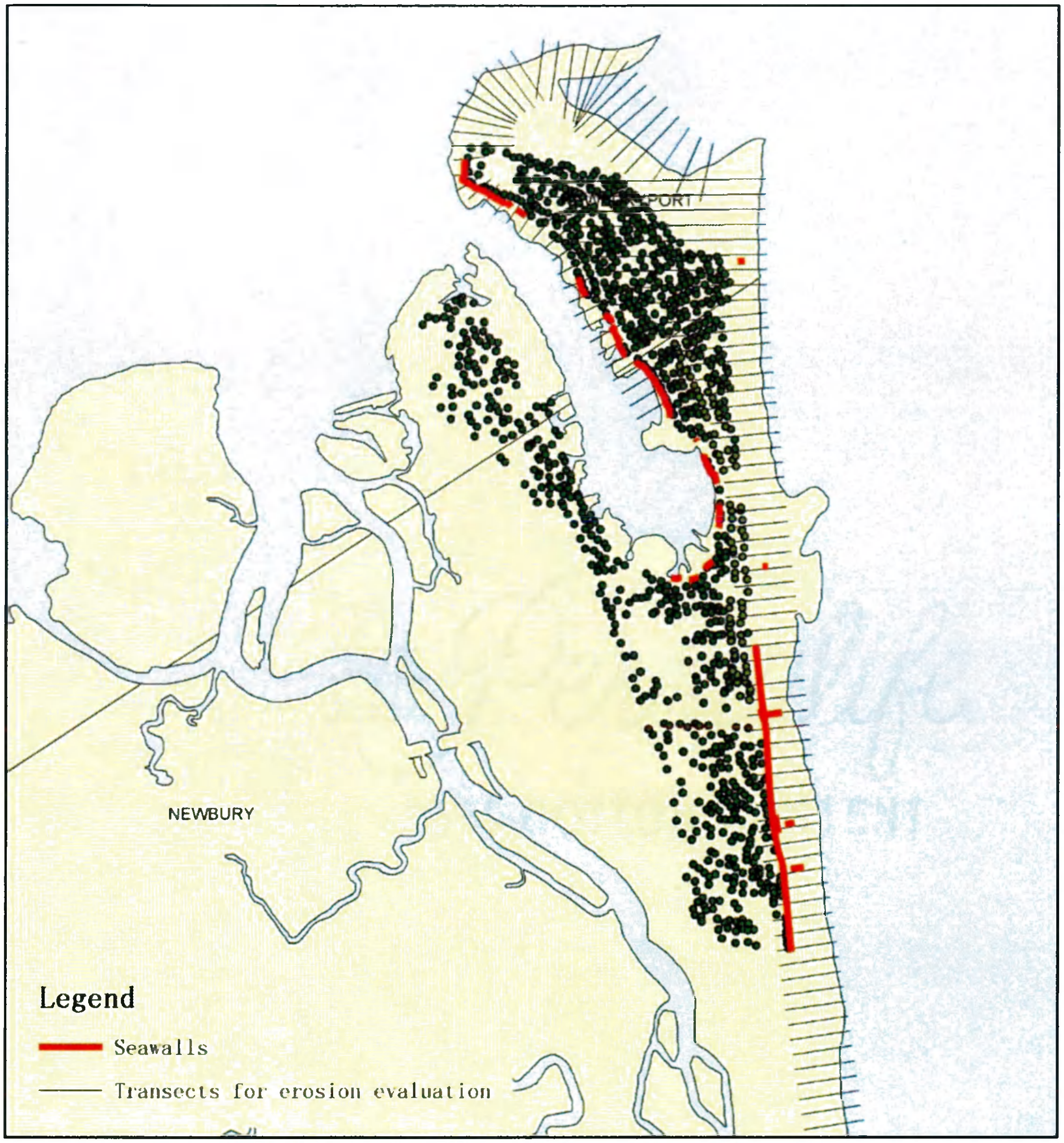

NEWBURY
Legend
Seawalls
Transects for erosion evaluation

Fig. 15: Private value of shoreline protection based on distance to the shoreline and type of structure; public, private or none. When compared to no protection structure, on average a property with a private structure is worth $20,000 more, while a property with a public structure is worth $70,000 more.

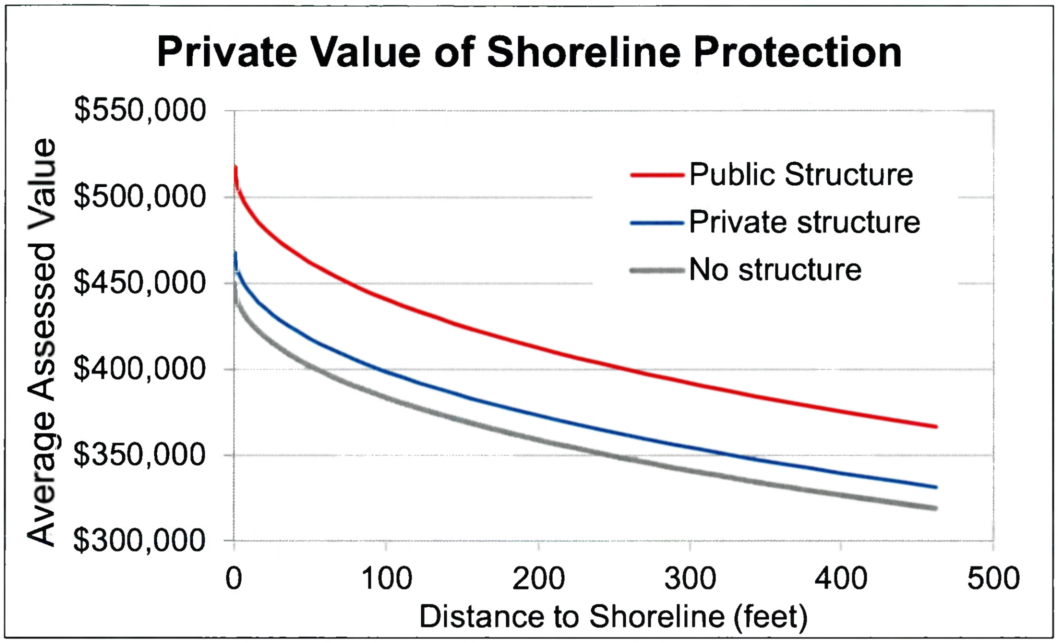

Private Value of Shoreline Protection
Average Assessed Value
$550,000
$500,000
$450,000
$400,000
$350,000
$300,000
0
100
200
300
400
500
Distance to Shoreline (feet)
Public Structure
Private structure
No structure

Fig. 16: Average assessed private value of elevated piling construction depending on distance of the property to shoreline. On average a home with piling construction when compared to a property without is worth $30,000 more.

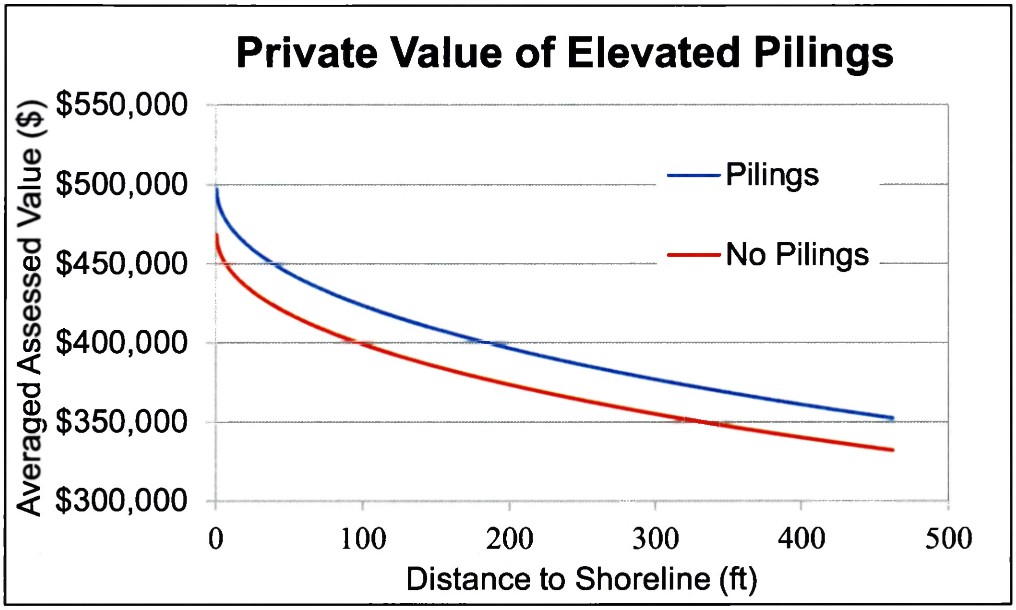

Private Value of Elevated Pilings
Averaged Assessed Value ($)
$550,000
$500,000
$450,000
$400,000
$350,000
$300,000
0
100
200
300
400
500
Distance to Shoreline (ft)
Pilings
No Pilings

Table 7: Literature review of similar Hedonic models in coastal areas. Table compares other HPM studies in coastal locales investigating the role of coastal erosion and/or associated risks. Variables of particular note include; Distance to the shore, Elevation, Erosion, Geotime, Shoreline Protection and Piling Construction.

Literature review of similar Hedonic models in coastal areas								
Author	Location	Paper focus	Distance to the shore	Elevation	Erosion	Shoreline Protection	Piling construction	Geotime
Jin et al., 2014	South Shore, MA	Shoreline protection	Negative	Significant	Significant	Significant		
Kriesel et al., 2000	Atlantic, Gulf and Pacific US coasts	Erosion and time to inundation	Negative	Positive	Positive	Positive		Positive
Landry & Hindsley, 2011	Tybee Island, GA	Beach and Dune Width	Negative		Not Significant			
Kriesel and Friedman 2002, 2003	several counties in SE Unites States	Beach Erosion Management	Not significant	Positive	Negative	Positive (front row)/Negative (other)		
Landry et al., 2003	Tybee Island, GA	Beach Erosion Management	Negative		Negative			
Eberbach and Hoagland, 2011	Sandwich, MA	Erosion risk	Negative		Negative	Positive		
Bin et al., 2011	four coastal counties, NC	Sea level rise	Negative	Not significant				
Atreya and Czajkowski, 2014	Galveston, TX	Flood Risk and amenity value	Negative			Positive		
Hoagland, Fallon and Jin	Plum Island, MA	Beach erosion and shoreline protection	Negative	Significant	Significant	Significant	Significant	Not significant

Table 8: Descriptive statistics of all variables in the Hedonic Pricing Model. Each variable has a statistical mean, standard deviation, minimum and maximum.

Variable	N	Mean	StdDev	Minimum	Maximum
Distance to shore	793	139.3	76.0	4.6	474.9
Elevation	736	3.5	1.3	1.1	8.5
Elevation^2	736	14.1	11.2	1.3	72.6
Lot size^2	793	70374179.9	121822551.0	3111696.0	1695298276.0
SQRT(Dist. To shore)	793	11.3	3.3	2.1	21.8
Age	434	48.3	30.1	-17.0	132.0
Basin	736	0.1	0.3	0.0	1.0
Beach	736	0.1	0.3	0.0	1.0
Backbarrier	736	0.1	0.2	0.0	1.0
Beds	793	2.6	0.9	1.0	8.0
Baths	793	1.5	0.7	0.0	4.5
Lot size	793	7160.8	4372.8	1764.0	41174.0
Finished area	793	1928.6	1038.2	254.0	7410.0
Newbury	736	0.5	0.5	0.0	1.0
Bungalow	793	0.0	0.1	0.0	1.0
Camp yr round	793	0.2	0.4	0.0	1.0
Cape	793	0.1	0.2	0.0	1.0
Colonial	793	0.1	0.3	0.0	1.0
Contemporary	793	0.1	0.3	0.0	1.0
Camp	793	0.1	0.3	0.0	1.0
Family converted	793	0.0	0.1	0.0	1.0
Family duplex	793	0.0	0.1	0.0	1.0
Old style	793	0.0	0.2	0.0	1.0
Old style colonial	793	0.0	0.1	0.0	1.0
Raised ranch	793	0.0	0.1	0.0	1.0
Ranch	793	0.1	0.3	0.0	1.0
LTE* distance ft	793	60.0	393.3	-401.0	1591.4
LTE* rate ft	793	0.3	2.9	-2.9	10.7
LTE* uncertainty	793	2.9	3.1	0.1	12.7
STE** distance ft	793	-31.0	164.2	-282.5	521.5
STE** rate ft	793	-0.6	5.3	-8.3	16.9
STE** uncertainty	793	9.2	10.0	0.1	69.9
AE flood zone	793	0.2	0.4	0.0	1.0
AO flood zone	793	0.1	0.3	0.0	1.0
Velocity flood zone	793	0.3	0.4	0.0	1.0
Marsh	793	0.3	0.4	0.0	1.0
Man made struc.	793	0.2	0.4	0.0	1.0
Sandbeach	793	0.4	0.5	0.0	1.0
Public shoreline protection	793	0.2	0.4	0.0	1.0
Private shoreline protection	793	0.3	0.5	0.0	1.0
Seawall 0-5 ft	793	0.0	0.1	0.0	1.0
Seawall 5-10 ft	793	0.0	0.1	0.0	1.0
Sea wall 10-15 ft	793	0.2	0.4	0.0	1.0
seawall	793	0.3	0.5	0.0	1.0
LTE Geotime	793	72.2	139.6	14.0	1482.4
STE Geotime	793	54.8	3.6	40.6	78.3
Total Value	793	412110.3	149659.9	187500.0	1142800.0
Sale Price	448	346462.9	250043.4	1.0	1866000.0
Piling	793	0.1	0.3	0.0	1.0
M1	793	0.1	0.3	0.0	1.0
M2	793	0.1	0.2	0.0	1.0
M3	793	0.1	0.3	0.0	1.0
M4	793	0.1	0.3	0.0	1.0
M5	793	0.1	0.3	0.0	1.0
M6	793	0.1	0.3	0.0	1.0
M7	793	0.1	0.3	0.0	1.0
M8	793	0.1	0.3	0.0	1.0
M9	793	0.1	0.3	0.0	1.0
M10	793	0.1	0.3	0.0	1.0

M11	793	0.1	0.3	0.0	1.0
Y90	793	0.0	0.1	0.0	1.0
Y91	793	0.0	0.1	0.0	1.0
Y92	793	0.0	0.2	0.0	1.0
Y93	793	0.0	0.1	0.0	1.0
Y94	793	0.0	0.2	0.0	1.0
Y95	793	0.0	0.2	0.0	1.0
Y96	793	0.0	0.2	0.0	1.0
Y97	793	0.0	0.2	0.0	1.0
Y98	793	0.0	0.2	0.0	1.0
Y99	793	0.0	0.2	0.0	1.0
Y00	793	0.0	0.2	0.0	1.0
Y01	793	0.0	0.2	0.0	1.0
Y02	793	0.1	0.2	0.0	1.0
Y03	793	0.0	0.2	0.0	1.0
Y04	793	0.1	0.2	0.0	1.0
Y05	793	0.0	0.2	0.0	1.0
Y06	793	0.0	0.2	0.0	1.0
Y07	793	0.1	0.2	0.0	1.0
Y08	793	0.0	0.2	0.0	1.0
Y09	793	0.0	0.2	0.0	1.0
Y10	793	0.0	0.2	0.0	1.0
Y11	793	0.1	0.3	0.0	1.0
Y12	793	0.1	0.3	0.0	1.0
Y13	793	0.1	0.3	0.0	1.0

Table 9: Hedonic Price Model Results. This table highlights the significant variables as indicated by t and p values. The significant variables have an output of parameter estimate, standard error, t value and Pr > |t| values.

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	12.37507	0.03854	321.11	<.0001
Newbury	0.09148	0.02006	4.56	<.0001
Beds	0.02182	0.00619	3.52	0.0005
Baths	0.08578	0.01044	8.22	<.0001
Lot_size	0.00002613	3.06E-06	8.54	<.0001
Fin_area	0.00011246	9.56E-06	11.76	<.0001
bungalow	-0.09486	0.03158	-3	0.0028
camp_y	-0.17337	0.0159	-10.9	<.0001
cape	-0.06622	0.02275	-2.91	0.0037
contemp	0.04845	0.02204	2.2	0.0282
camp	-0.21111	0.01954	-10.81	<.0001
family_c	-0.15224	0.03861	-3.94	<.0001
old_style	-0.05523	0.02767	-2	0.0463
Ranch	-0.14007	0.01408	-9.95	<.0001
elevat2	0.00115	0.0005114	2.24	0.0253
lot2	-4.91E-10	8.39E-11	-5.85	<.0001
dist3	-0.01397	0.00216	-6.47	<.0001
Basin	0.14721	0.02017	7.3	<.0001
Beach	0.18897	0.02329	8.12	<.0001
BackBarrie	0.13202	0.02614	5.05	<.0001
LT_DIST_FT	0.00053874	0.000109	4.94	<.0001
LT_RATE_FT	-0.04133	0.01042	-3.97	<.0001
LT_UNCERT	-0.02702	0.00744	-3.63	0.0003
ST_DIST_FT	-0.00098747	0.0005513	-1.79	0.0737
ST_RATE_FT	0.03649	0.01696	2.15	0.0318
ST_UNCERT	0.00337	0.00148	2.27	0.0235
VE_ZONE	0.03378	0.01413	2.39	0.0171
marsh	0.07386	0.01442	5.12	<.0001
public	0.1309	0.0193	6.78	<.0001
seawall	0.04955	0.01358	3.65	0.0003
piling	0.05521	0.01855	2.98	0.003
M2	-0.04584	0.02207	-2.08	0.0382
M11	0.03418	0.0182	1.88	0.0607
Y08	0.06182	0.03184	1.94	0.0526
Y12	0.03757	0.01532	2.45	0.0145

Table 10: Binary variable property cost and 95% confidence intervals. Results are directly derived from variable coefficients, mean standard error as derived from the regression results shown in table 3. Each binary variable's cost is calculated from utilizing the presence of that variable (1) as opposed to the mean of the variable (somewhere from 0-1, see Table 2). This calculation shows the specific increase or decrease in value from an average property on Plum Island.

Binary variable costs with 95% confidence interval			
Variable	Property cost	95% confidence interval	
Newbury	$412,050	$410,428	$413,678
bungalow	$355,840	$353,002	$358,701
camp_y	$343,858	$341,532	$346,199
cape	$374,114	$374,891	$373,338
contemp	$419,740	$418,545	$420,938
camp (seasonal)	$327,191	$324,599	$329,803
family_c (family camp)	$335,801	$331,551	$340,105
old_style	$375,011	$373,927	$376,098
Ranch	$343,079	$341,212	$344,956
Basin	$448,775	$446,072	$451,495
Beach	$481,973	$477,711	$486,273
BackBarrier	$452,733	$450,018	$455,464
marsh	$409,258	$408,347	$410,171
public seawall	$439,019	$436,587	$441,465
private seawall	$403,457	$403,145	$403,768
M2 (Feb)	$376,837	$376,179	$377,496
M11 (Nov)	$406,934	$406,314	$407,555
Y08	$418,174	$417,081	$419,271
Y12	$406,346	$405,742	$406,952
Piling	$414,651	$413,657	$415,648
Velocity flood zone	$406,303	$405,907	$406,687
ST_RT_FT	$395,449.58	$394,373.30	$396,525.87
LT_RT_FT	$376,571.33	$368,385	$384,757
Avg. property	$392,806		

Conclusions

The coupling of long-term barrier island stability, short-term cycles of beach erosion and accretion, and dense human development makes Plum Island an ideal site to study shoreline change and resultant economic impacts on the coastal housing market. The presence of contrasting shoreline change trends over different timescales means that mitigation structures need to be evaluated in terms of both their long- and short- term impacts and feasibility, as a structure that may be advantageous over a 20-year period is not useful in a 100–year timeframe, or vice versa. This contrast is strong enough that the perception of homeowners, as reflected in the hedonic pricing model presented in Chapter 2 of this thesis, is not impacted by short-term erosion issues. The geographic zone of impact of the recent erosion is only an issue for 8–10 houses, whereas the other ~1000 homes on the Island remain safe and secure each time the erosion hotspot forms and migrates along the shore.

Shoreline change of northern Plum Island since jetty construction reflects cyclical erosion trends through stable-inlet processes, open-channel shifting and storm wave refraction, which together drive onshore and alongshore sediment migration trends. There are several important conclusions from this thesis regarding the utilization of economic models to determine the value of environmental variables and the importance of characterizing shorelines on different timescales to provide for a full comprehension of these dynamic systems.

Shoreline change: Mitigation structures

Plum Island has received ample media attention from a policy standpoint because, over the last seven years, severe erosion along Center Island and Annapolis Way has culminated in the loss of 12 homes. This study indicates that this erosion is only temporary, and that there have been four instances of localized erosion shifting the shoreline 80–100 m landward since jetty completion in 1914.

Since the pattern of erosion on Plum Island has been characterized, now the societal challenge needs to be addressed. The problem on Plum Island is that the cycles of erosion are too long (~25-30 years) for most homeowners on the front lines of the erosion to remember that the beach will eventually accrete back to a healthy state as the erosion hotspot migrates down the beach and eventually dissipates. This may lead to poor decision making for short term mitigation solutions, including the installation of hard shoreline protection structures. This has been the case on Plum Island since the installation of the jetties on the Merrimack River Inlet: cycles of erosion prompt mitigation strategies which tend to be permanent changes to the beach. The engineering on Plum Island began in the 1950s (Table 2, Ch. 1) with the construction of several groins downdrift of the jetties. These groins were constructed to retain sand in hotspot areas instead of allowing further transport to the downdrift beach, which potentially helped the specific erosion issue back in the 1950s. However, 60 years since construction, the groins are slumped and, at best, are doing little to help the beach. Even worse, during the most recent cycle of erosion the groins seem to have exacerbated hotspot erosion along southern Annapolis Way by funneling wave energy between them and preventing the gradual migration of a wider and possibly shallower hotspot along the beach.

Most recently, in response to the issues over the last two years, the entire section of beach south of Center Island to Fordham Way has been stabilized by rip-rap revetments. This foredune armoring promotes scour at the base of the revetments. The scour not only erodes the beach and lowers the overall profile, but also promotes slumping of the revetment rocks, altering the desired geometry and thereby promoting further scour and a negative feedback loop only solved by continual maintenance and nourishment at growing cost to the homeowners.

Based on this study, there are two sustainable mitigation approaches that would enhance the longevity of the island as a whole, though would not necessarily benefit individual homes located within the epicenter of periodic areas of focused erosion. Both approaches would require major changes to coastal policy and/or the removal of current hard structures, some of which were illegally emplaced in direct disregard for policy.

The first recommendation is to remove all of the groins on the island. The groins appear to exacerbate cycles of erosion if the offshore bar happens to be adjacent to the groin. The contrasting transport directions (dominant to the south due to northeast storms, but prevailing to the north) makes it so that the groins are completely useless and create an artificial low tide terrace on the north side of groins for northeast storms to drive up, like a ramp onto the dunes and beachfront homes. Furthermore, the large tidal range on the island makes it such that the groins are almost entirely underwater during a high storm tide; the net effect under all scenarios is purely a slow exacerbation of the cycles of erosion that are already occurring due to the Merrimack River Inlet jetties.

A second recommendation is more in regards to a policy implementation on the island. Rip-rap revetments should not be allowed. The rip rap is emplaced during periods of severe erosion and then buried after the erosive cycle is over. However, once the rip rap is installed, the beach is permanently impacted and degraded. The scour at the revetment base can permanently alter the natural beach profile and eventual slumping causes rock debris to be moved out on the beach face. Instead of using rock revetments, homeowners should only be allowed to install temporary soft structures, with a preference towards beach nourishment. The latter could be done during times of bad erosion and, when the beach is healthy, allow it to accrete naturally towards its long-term steady-state shoreline position. Beach nourishment efforts have been successful at many locations across the United States; Ocean City MD, Cocoa beach FL, Menauhant Beach, MA and Virginia Beach, VA have all had success in maintaining healthy beaches through periodic nourishment (Houston & Dean, 2013).

Hedonic price model

The results from the hedonic regression model provided important information about the relationship between variables influencing house price and the shoreline change patterns on Plum Island. The model proved several variables are significant, most notably shoreline protection and raised piling construction. However, the most striking finding was the lack of correlation of geotime with housing values. This was surprising because of how much recent erosion is severely impacting a row of 10–20 homes. While certainly newsworthy (CNN's Anderson Cooper had a national news report based from one of these homes during a nor'easter in early 2015), this erosion is highly localized; when looking at the island as a whole, or even all beachfront homes, erosion is not a significant factor in property values.

The importance of shoreline protection to homeowners was preferential to the public structures. This strong preference for protection without responsibility provides insight to the opinions of many coastal property owners. Owners want the view (the location with amenities), but will not accept the consequences associated with erosion risk. They therefore do not want to pay for it. Owners likely believe that they have contributed through the high tax base of coastal communities. However, in places like Plum island where there is periodic risk in small areas the coast of protection for 8-10 houses is far more than the cost of protecting those properties that are in serious risk of erosion.

Raised piling construction is now required for all homes in a high-risk flood zone, and the economic benefit is evident in our price model. One of the problems with this policy is that most homes have already been built, and therefore property owners will not invest to have these structures placed on pilings. Properties that are currently on traditional foundations are at a higher risk for storm surge and flooding damages, but the economic advantage of raised pilings (~$30,000) is less than the cost to move a property to pilings. Hence, this study indicates that hedonic models in other coastal areas should include the piling variable because, in an area with uniform erosion risk, the cost benefit from piling construction may be comparable to the cost of moving a home.

Future work

It is the nature of any scientific research that more questions will arise during a study prompting future work. In the following sections I detail several suggestions for future work both on individual fronts with hedonic models and geologic shoreline change, as well as future combined multi-disciplinary efforts.

Geologic shoreline change

This thesis presents a comprehensive shoreline-change and sediment fluctuation assessment of northern Plum Island. The dual analysis of historical and recent shoreline change have enabled the development of a conceptual model to explain the driving mechanisms of cyclical erosion on the northern 3 km of Plum Island. The framework illustrated by the conceptual model could be reinforced through a combination of additional field work and coupled hydrodynamic and sediment-transport modeling. The field work would be particularly focused on collecting bathymetric surveys of the Merrimack Inlet ebb-tidal delta and southern migrating bars. The scale of the project would determine how much new data would be required. In a large scale effort, an annual, seasonal or even monthly survey would be ideal. However a single survey would provide enough baseline bathymetry data to create a simplified model which may well be enough to further support the proposed conceptual model.

The model would utilize the bathymetric data collected in the survey and apply characteristic daily and extreme events to show potential change scenarios in the delta, nearshore and onshore to better characterize the cycles of erosion. A combined survey and modeling effort would enable both a more precise approximation of the duration of erosive cycles as well as the particular drivers that could alter this timing. Through this model, it would be crucial to try to pinpoint the influence of storm severity in both the timing of cycles and magnitude/duration of those cycles. This is one of the most unknown aspects about Plum Island because of the dual transport directions on the northern end of the island. In a typical year, there is dominant transport to the south from northeast winter storms, but wave refraction around the Merrimack River Inlet ebb-tidal delta causes local reversal in transport direction. Moreover, prevailing winds are from the south to the north, leading to northerly longshore transport during quiet water conditions. This discrepancy means that storm severity each year alters the rate, movement and orientation of the offshore bar and sediment transport patterns along the island shoreface, thus dictating the placement and duration of erosion hotspot. This variation in sediment bypassing does not change the mechanisms for the conceptual model, but could create a smaller or larger cycle of erosion and accretion. Lastly, this model would be very beneficial in determining the exact influence of groins and perhaps provide an indication of alternative mitigation strategies moving forward.

Hedonic regression models

A first step of future economic modeling efforts is to apply our model analyzing the economic influence on the housing market onto other coastal locales. This regression model is a proven tool through this study on Plum Island, but now could be applied in other areas experiencing coastal erosion. Using different study sites could provide indications as to both the continued or varied significance of the shoreline protection and raised piling variables and the particular erosion risk and time to inundation for specific locations.

This large range of inundation risk on Plum Island is clearly linked to the location of the most recent erosion hotspot. This raises a key question: Is the development of Plum Island linked to previous episodes of hotspot erosion dictating the safe or hazardous portions of the island? This study would also be based on the same hedonic regression model, but the key variables of interest would be the location of each home and the date of initial construction. This would essentially map the development of the island over time. By comparing this development timeline to our historic shoreline change record, we could determine if localized cyclical erosion played an important role in the geographic development of the island.

In addition to running our hedonic model with different variables or in different locations, there are many ways to utilize the data we already have to answer economic and policy questions in Plum Island and elsewhere. The values we have determined for shoreline protection structures and raised pilings could be applied to other sites as a benchmark to analyze the financial implications of policy decisions for both shoreline protection and piling construction for homeowners. This would be particularly beneficial in determining areas that policy change should be implemented either due to high erosion rates and/or a high tax base from infrastructure. In moving forward with the results specific to Plum Island, outreach to the Massachusetts Coastal Zone Management agency and Department of Environmental Protection is needed to properly apply our findings to future management. A final step would be to investigate the economic effects of educating property owners on the geologic influence of cyclical erosion on housing values and the positive/negative effects of erosion mitigation structures.

Multidisciplinary coastal change analysis

A unique feature of this thesis is the integration of the social and natural sciences to address questions surrounding coastal erosion which either field would fail to achieve in isolation. This study linking a hedonic economic regression model to a comprehensive shoreline-change analysis is a useful tool in determining the value of coastal homes during a time of accelerated sea-level rise and potentially enhanced storminess. A key finding from this multidisciplinary study is that certain environmental factors that were anticipated to be economically significant are not because of the unique patterns of geologically controlled shoreline erosion and accretion on Plum Island. This approach could be easily replicated in other coastal locales to determine the specific economic impact of certain variables that is now clear are very dependent on the shoreline change characteristics of that particular locale. Potential sites include highly developed areas like the New Jersey shore or Virginia Beach, where the presence of vast infrastructure proximal to the beach represents an enormous economic risk. Other sites, like Hatteras Island in the outer banks of North Carolina, would provide insight to the amount of economic risk where there is not an enormous tax base backing hard structure mitigation or beach nourishment projects. These potential sites do not have the bi-directional (cyclical) shoreline change patterns of Plum Island, which would allow the hedonic model to easily determine variables of interest and corresponding dollar value amounts.

Coupling economic models and geologic shoreline analyses enables a connection between two otherwise separate entities that should both be accounted for when implementing policy in coastal areas. Without the insight of a comprehensive geologic assessment, an economic model may not produce accurate results because it is not capturing the full characteristics of a particular coastal system. On the other hand, shoreline change assessments by themselves, without any accompanying social science evaluation (as has been done for dozens of years throughout academia and government), is highly unfortunate in that is fails to directly and quantitatively apply that knowledge for the benefit of coastal property owners and policy makers.

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